Selected LOFAR Science Slides

For illustration of LOFAR science – if disseminated further, please preserve references wherever possible. Materials include contributions from many friends and colleagues, in addition to my own.

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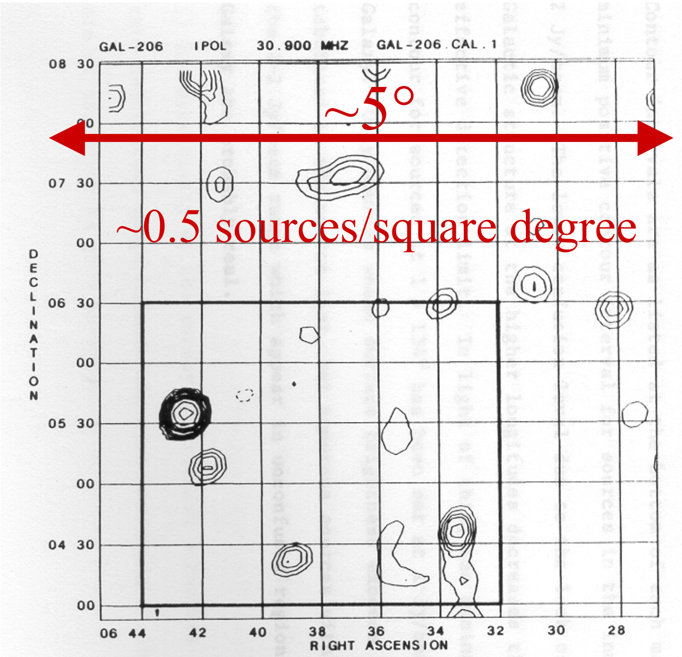
Comparison of Low Frequency Capabilities (past vs. present)

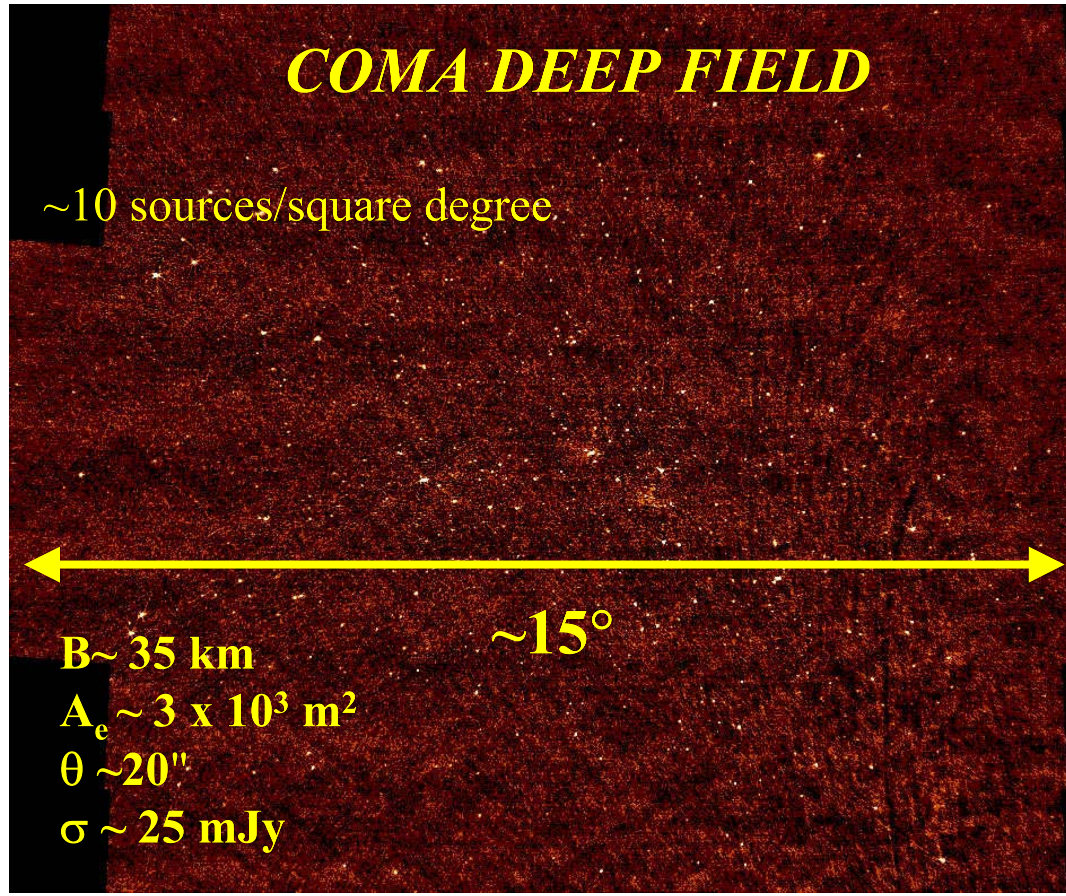
Clark Lake (30 MHz)



Kassim 1989

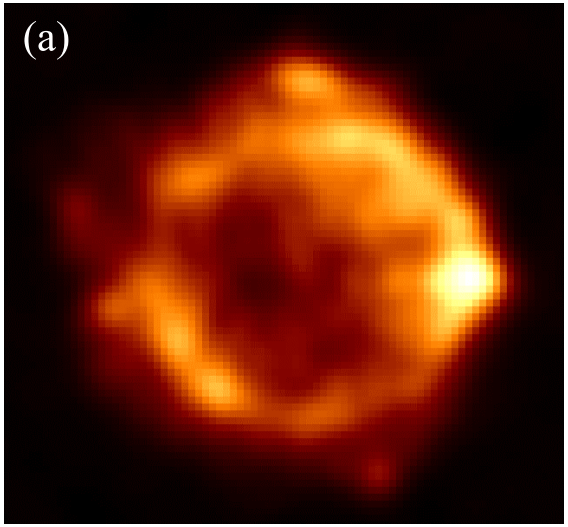
- B ~ 3 km
- $A_e \sim 3 \times 10^3$ m^2
- θ ~ 15’ (900")
- σ ~ 1 Jy

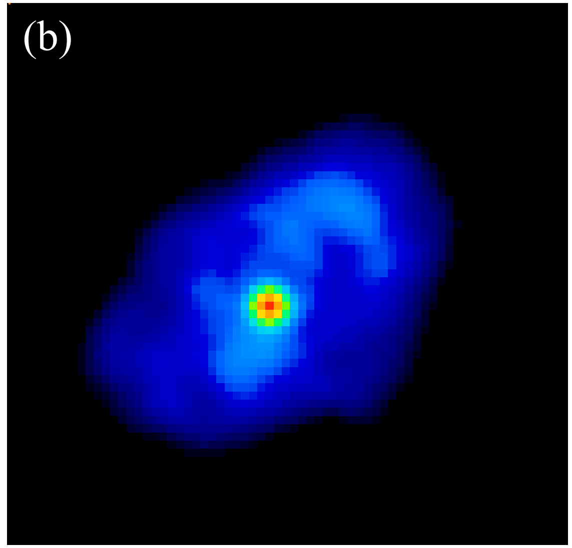
VLA (74 MHz)

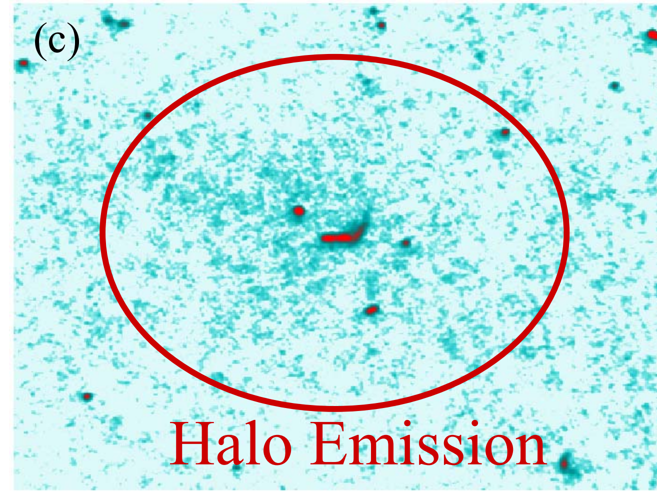


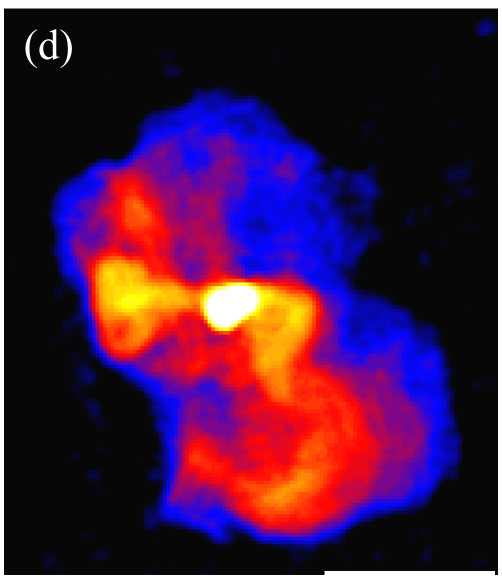
Enßlin *et al*. 1999

Results from VLA 74 MHz System



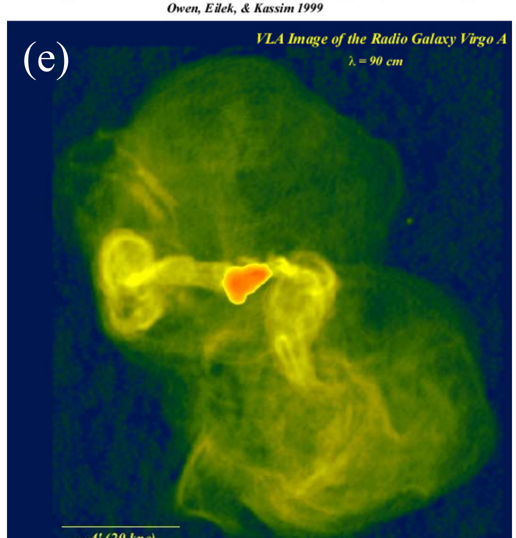






74 MHz

The Virgo Cluster and the M87 Radio Halo: Outflow, not Cooling Flow
Owen, Eilek, & Kassim 1999



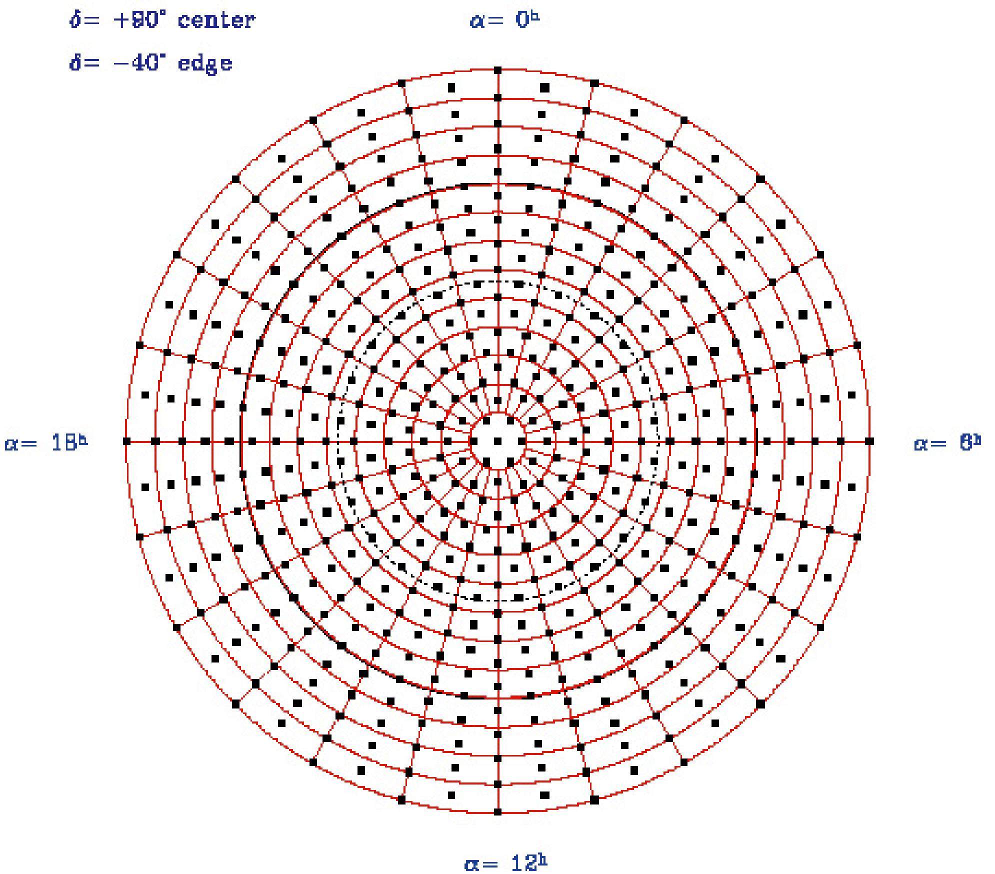
327 MHz

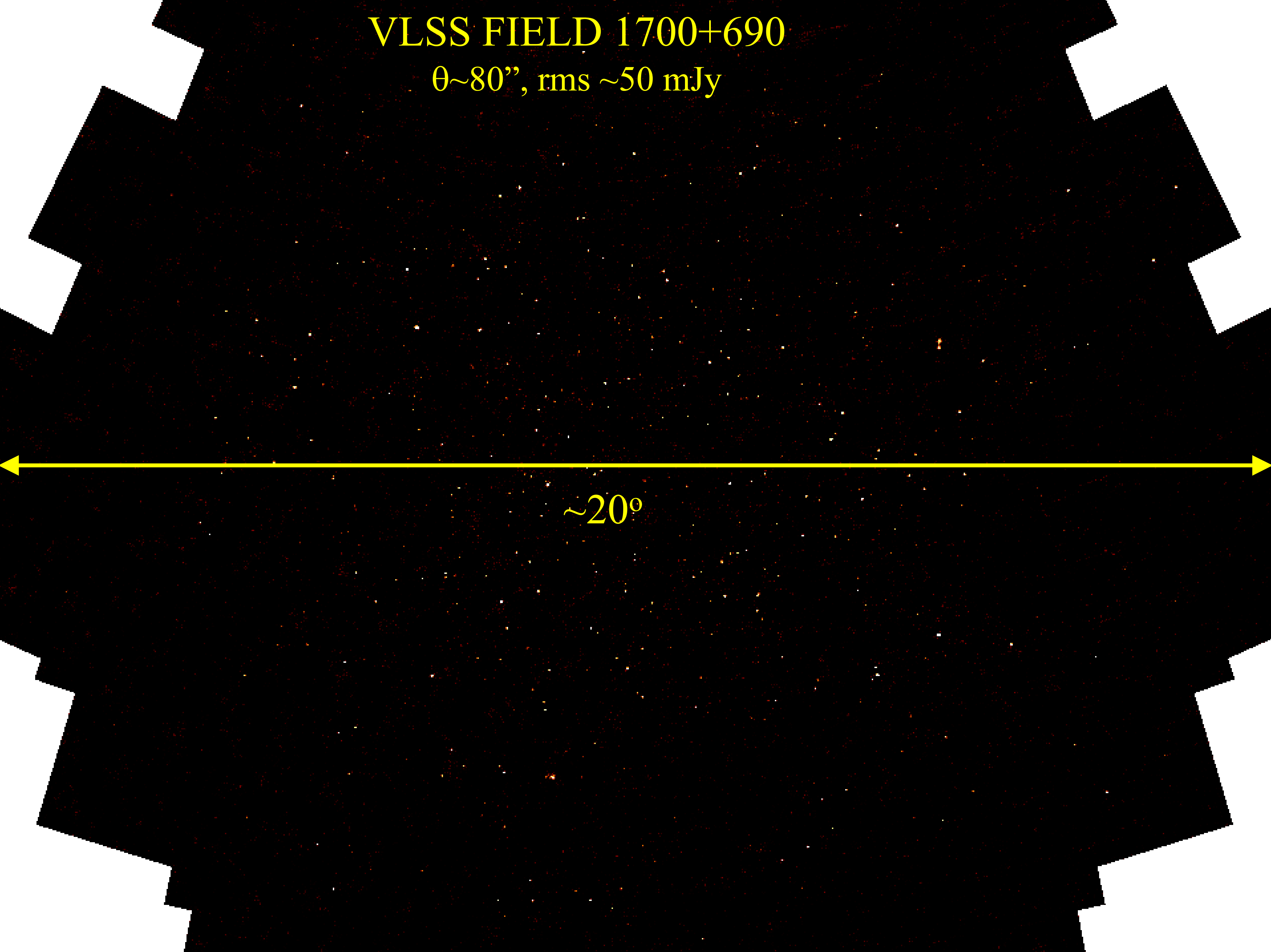
- (a,b) shock physics of supernova remnants (a: Cas A, Kassim *et al*. 1995; b: Crab Nebula, Bietenholz *et al*. 1997)
- (c) emission from relics & clusters of galaxies (Enßlin et al. 1999; Kassim et al. 1999, 2000)
- (d,e) radio galaxies & halos (Kassim et al. 1993; Owen et al. 1999, 2000)

VLA Low Frequency Sky Survey
(VLSS - formerly known as 4MASS)
Precursor to All-sky Surveying With LOFAR

- Deepest & largest LF survey
  - N ~ 10^5 sources in 10.3 sr – 80% of sky
  - Statistically useful samples of rare sources
    - Large, unbiased samples of steep spectrum sources
  - Key radio galaxy sample immune from beaming effects
    - Dominated by isotropic emission
    - Unbiased view of parent populations for unification models
- Important calibration grid for VLA, GMRT, & eventually LOFAR (Perley, Condon, Lane, Cohen, et al)

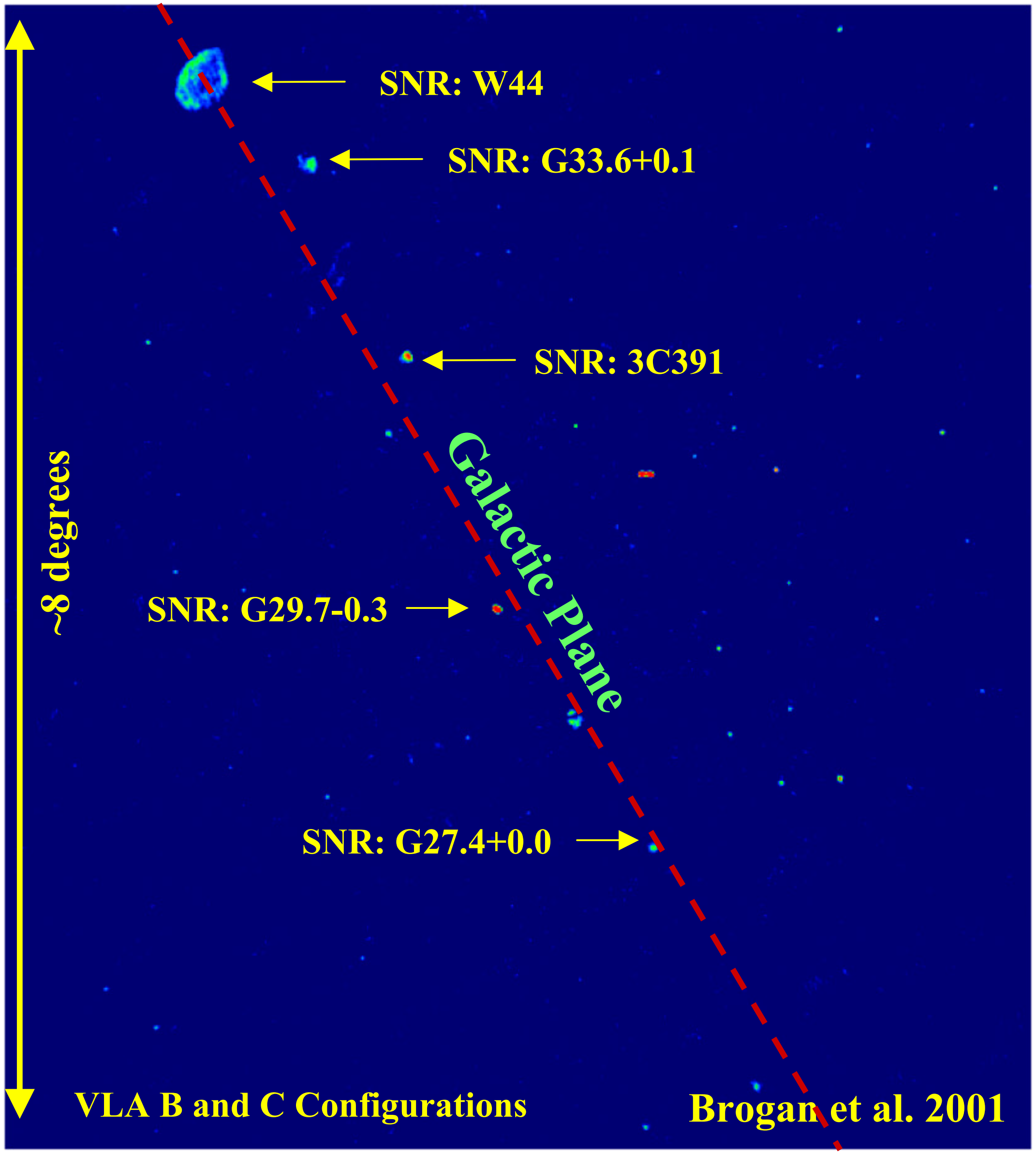
VLSS Field Centers




VLSS FIELD 1700+690
θ~80”, rms ~50 mJy
~20º

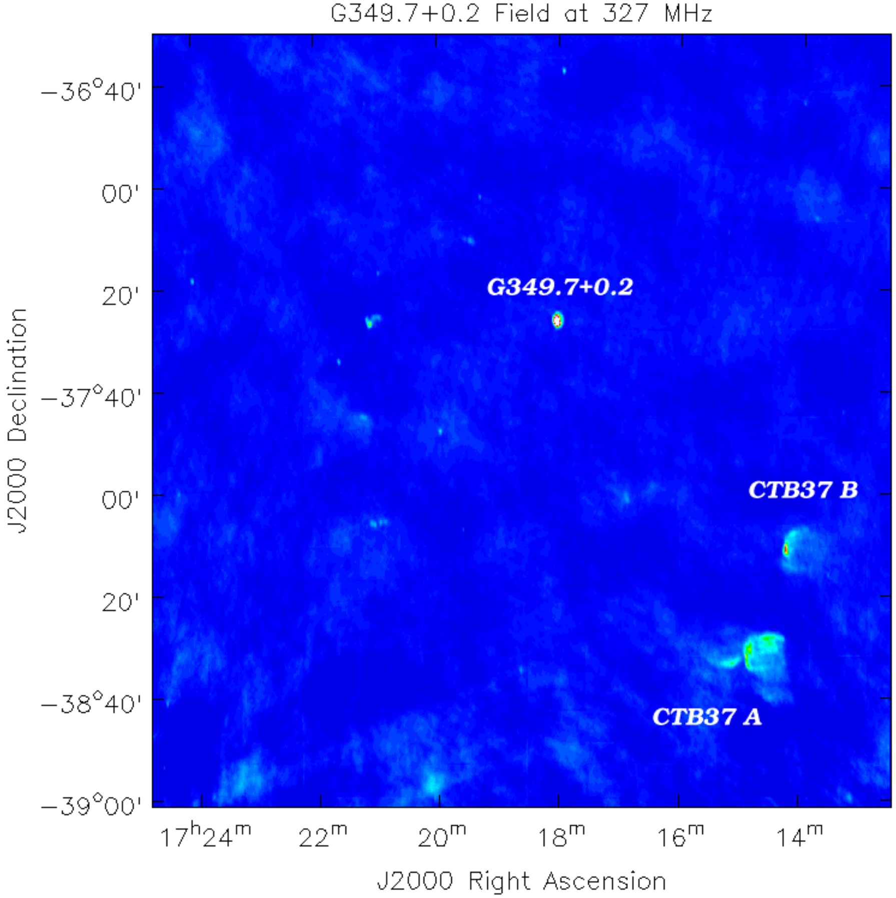
Galactic Supernova Remnants at 74 MHz

(courtesy C. Brogan)

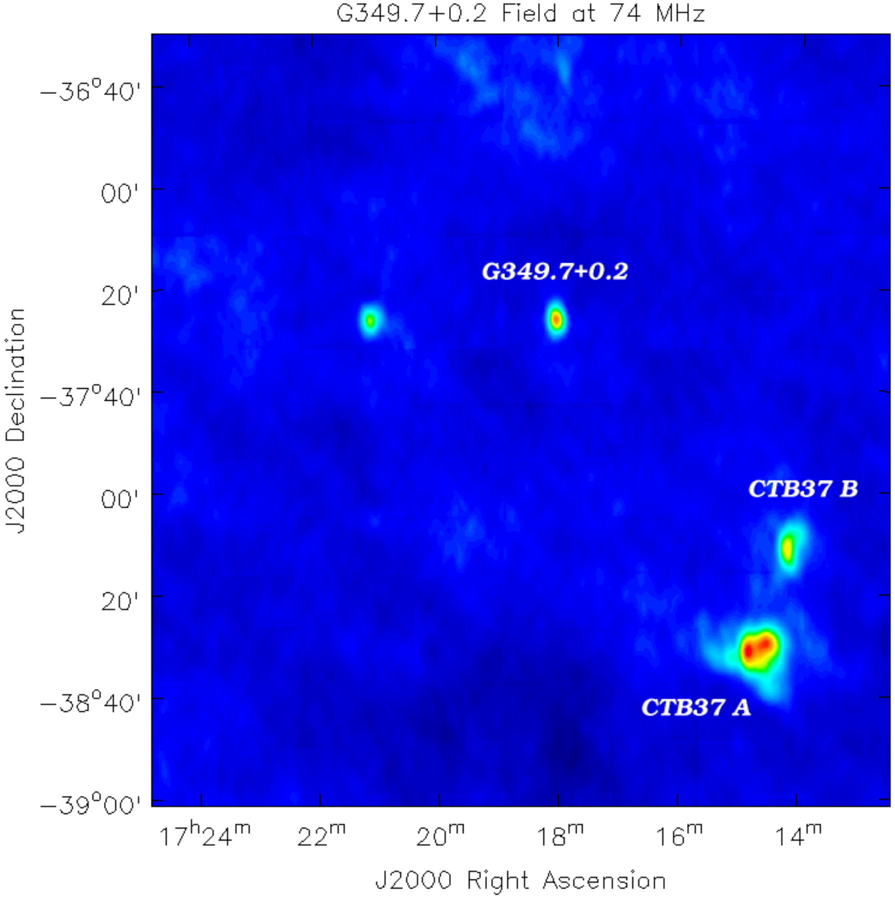


74 MHz VLA: Investigating SNRs & the ISM
(images courtesy C. Brogan)

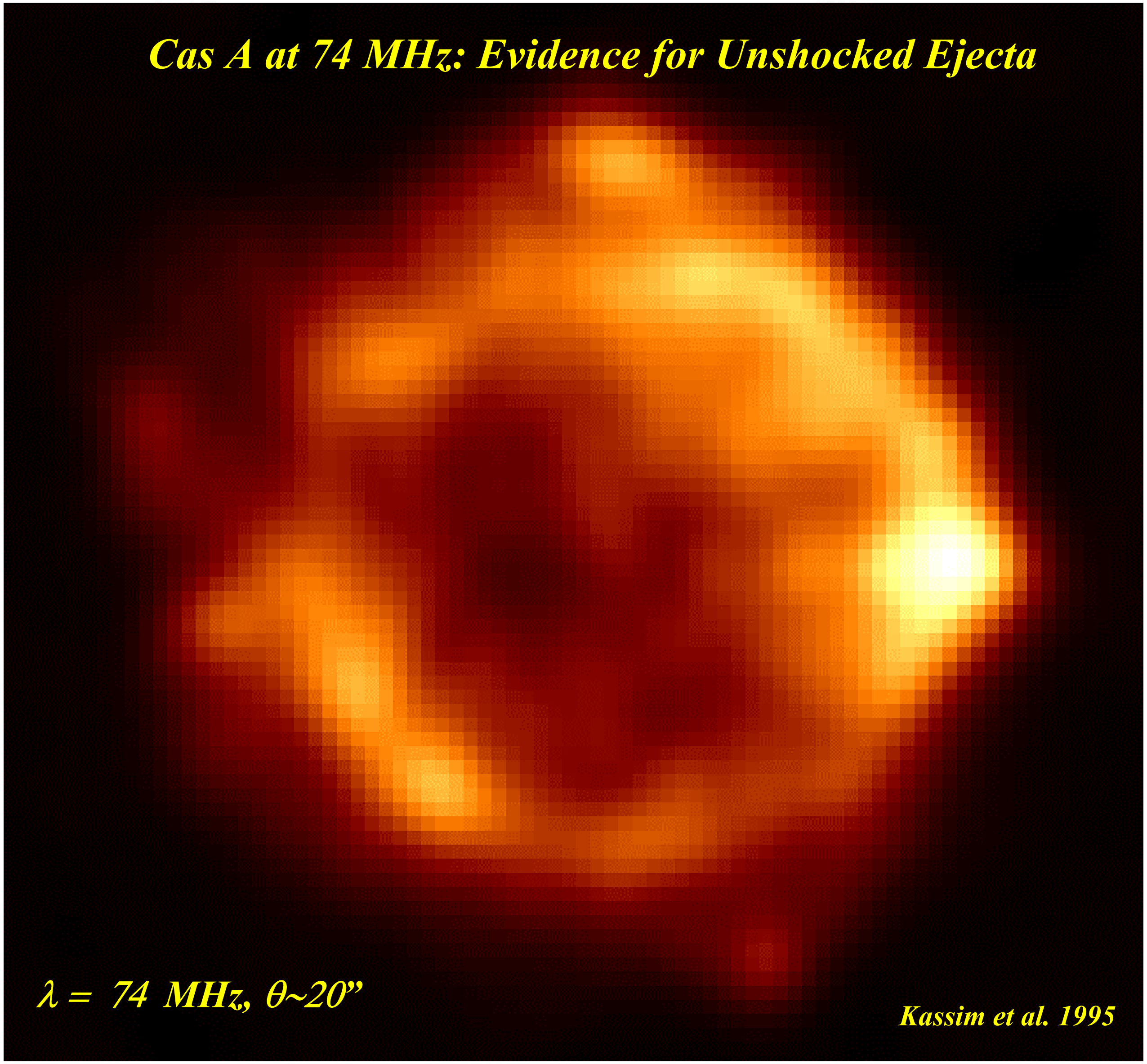
G349.7+0.2 at 327 MHz



G349.7+0.2 at 74 MHz

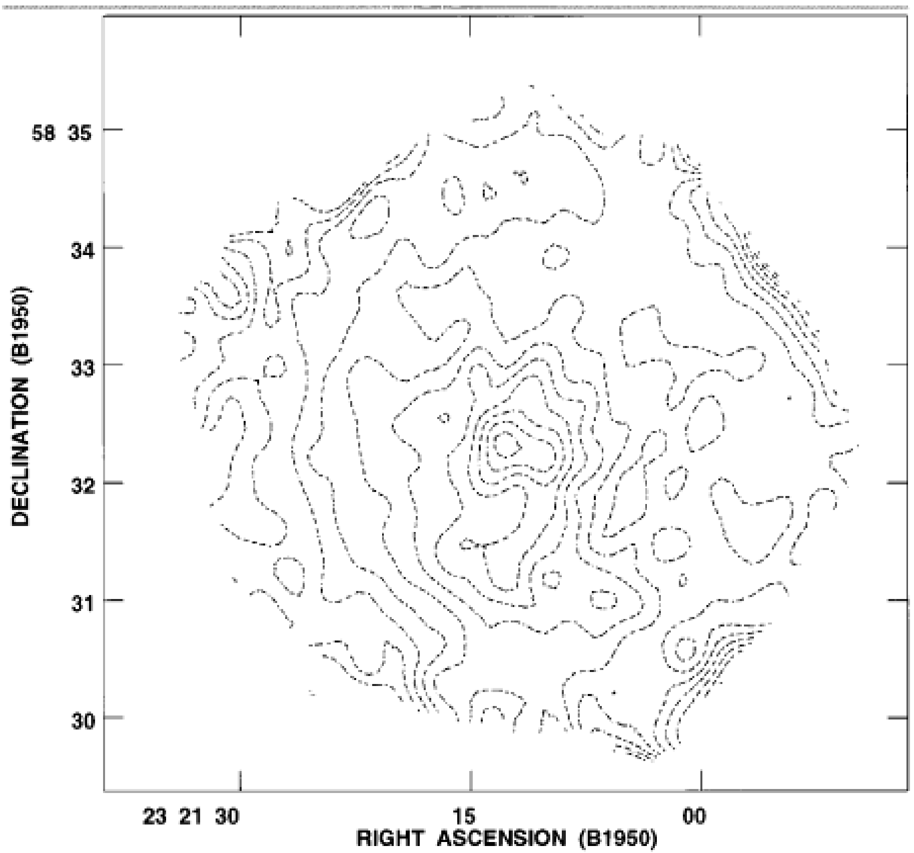


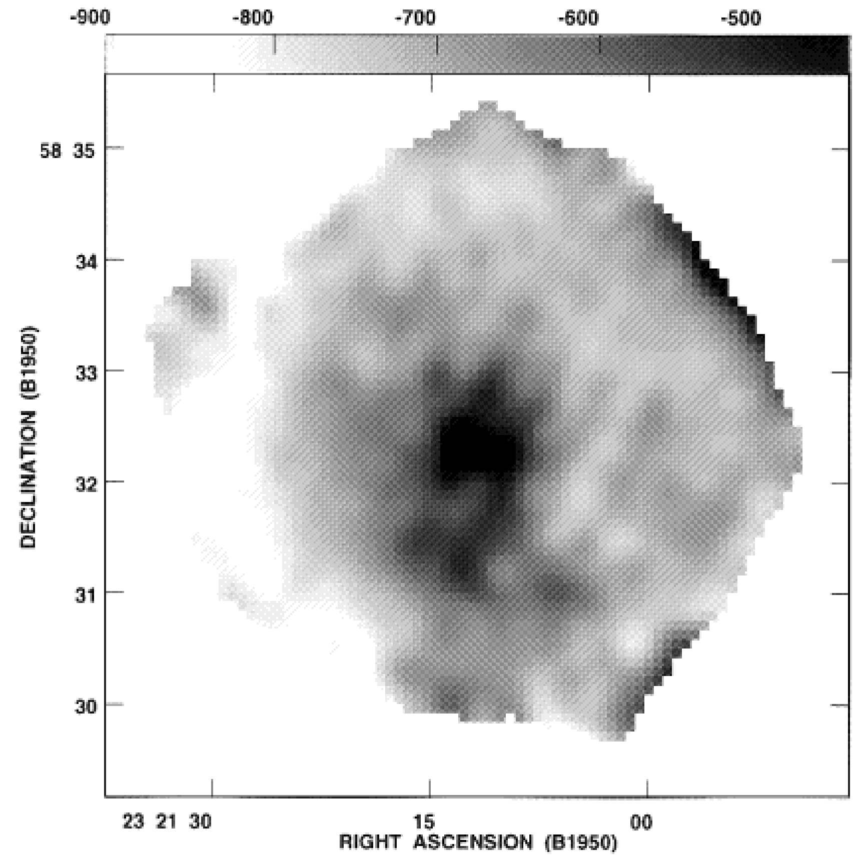
SNR Cas A at 74 MHz



Unshocked Ejecta Inside Cas A

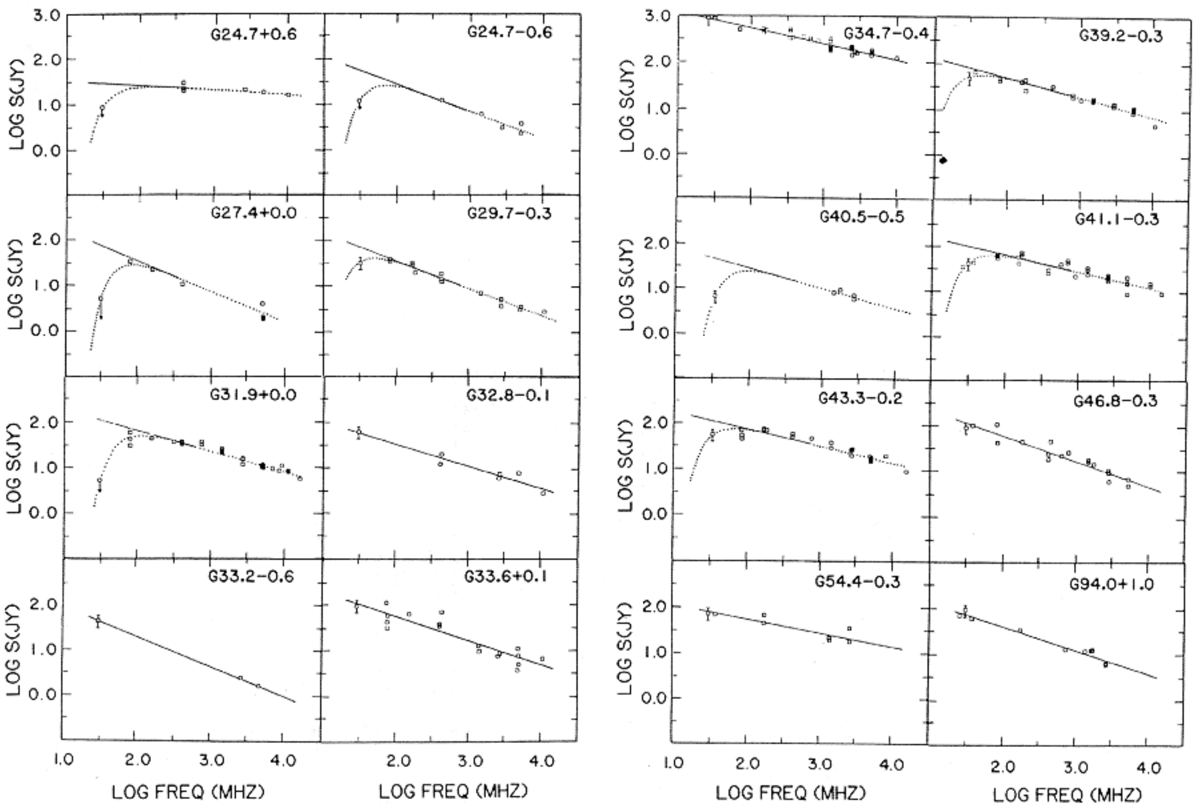
74/330 MHz spectral index





(Kassim et al. 1995, Delaney & Rudnick in preparation)

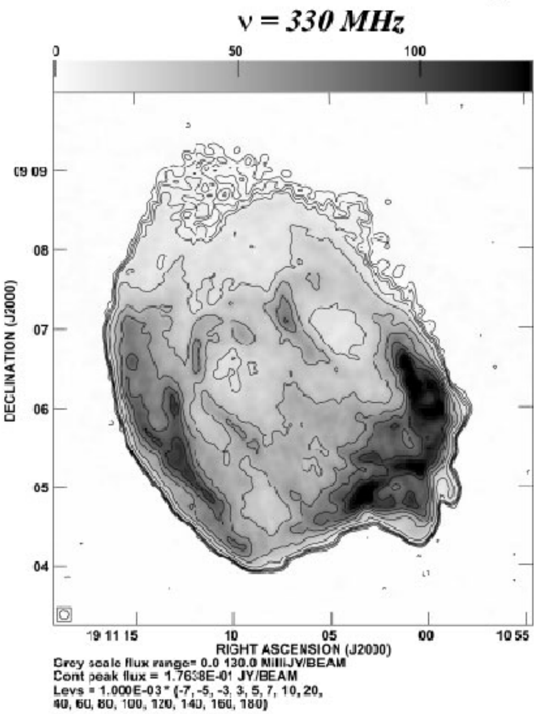
Patchy Absorption Towards Galactic SNRs & the Distribution of Ionized Gas in the ISM

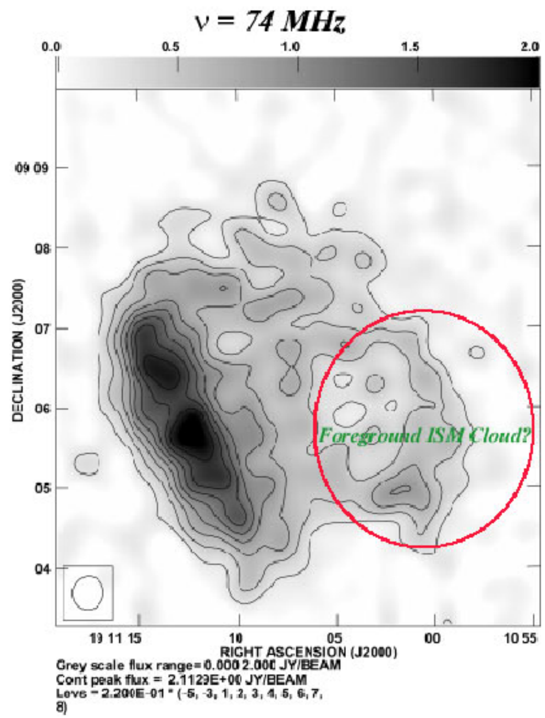


(Kassim 1989)

- Many, but not all, SNRs show low ν continuum turnovers.
- Previous low ν studies have been limited to integrated spectra by the poor angular resolution and sensitivity.
- LOFAR will revolutionize these absorption studies and expand to utilize xgal background sources for scattering studies.

Free-Free absorption from the ISM: W49B

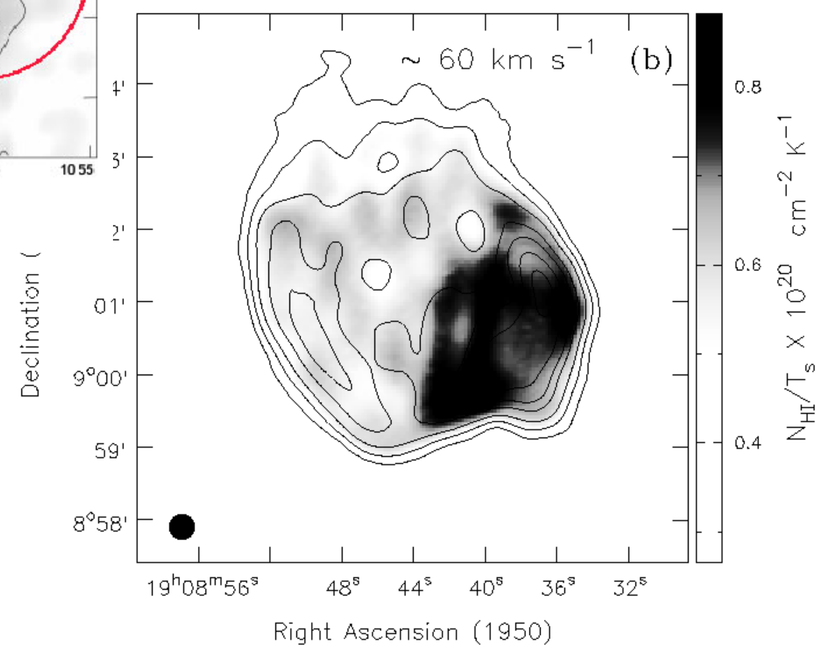




Lacey et al (2001)

First example of spatially resolved thermal absorption towards a Galactic SNR.

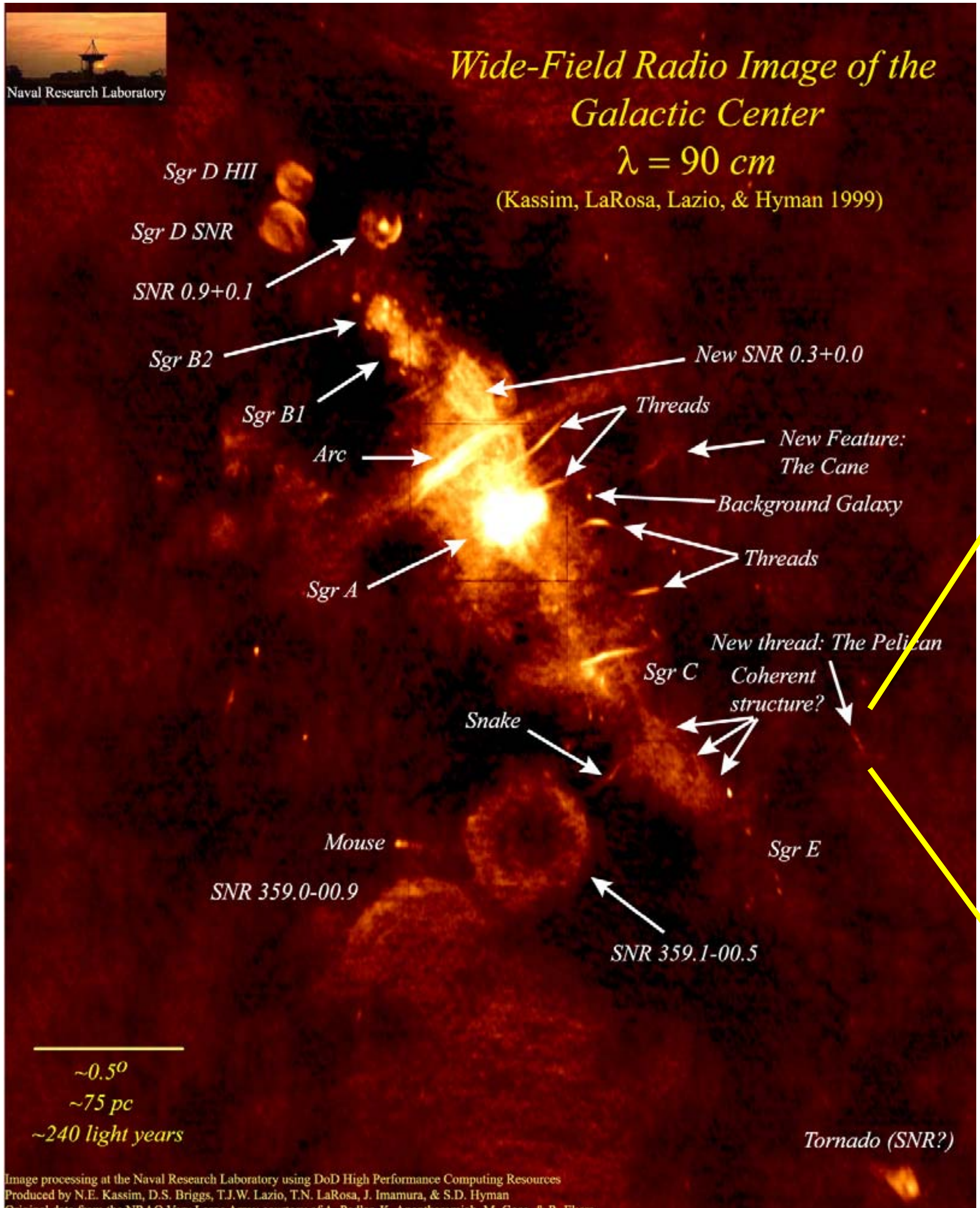
HI



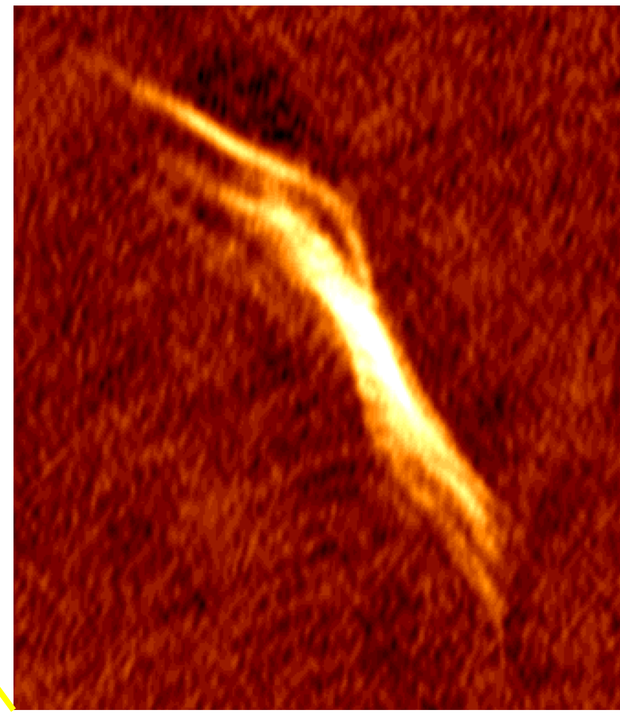
Brogan & Troland (2001)

Radio Recombination line H134α observed at ~65 km/s (*Downes & Wilson 1974*)

330 MHz Galactic Center

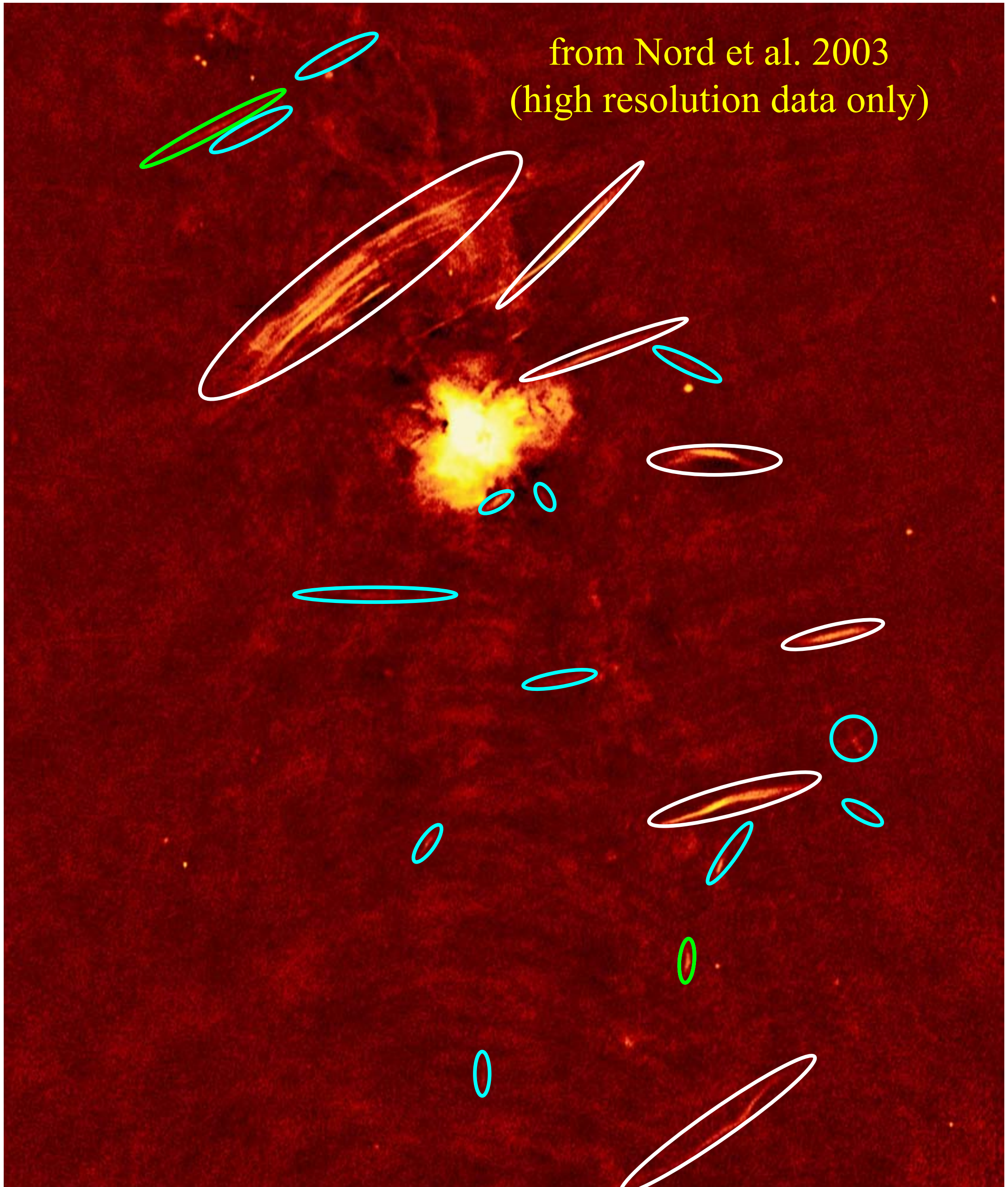


New GC non-thermal filament:
"The Pelican"



(Lang, Anantharamaiah, et al. 1999)

(Kassim et al. 1999, La Rosa et a. 2000)



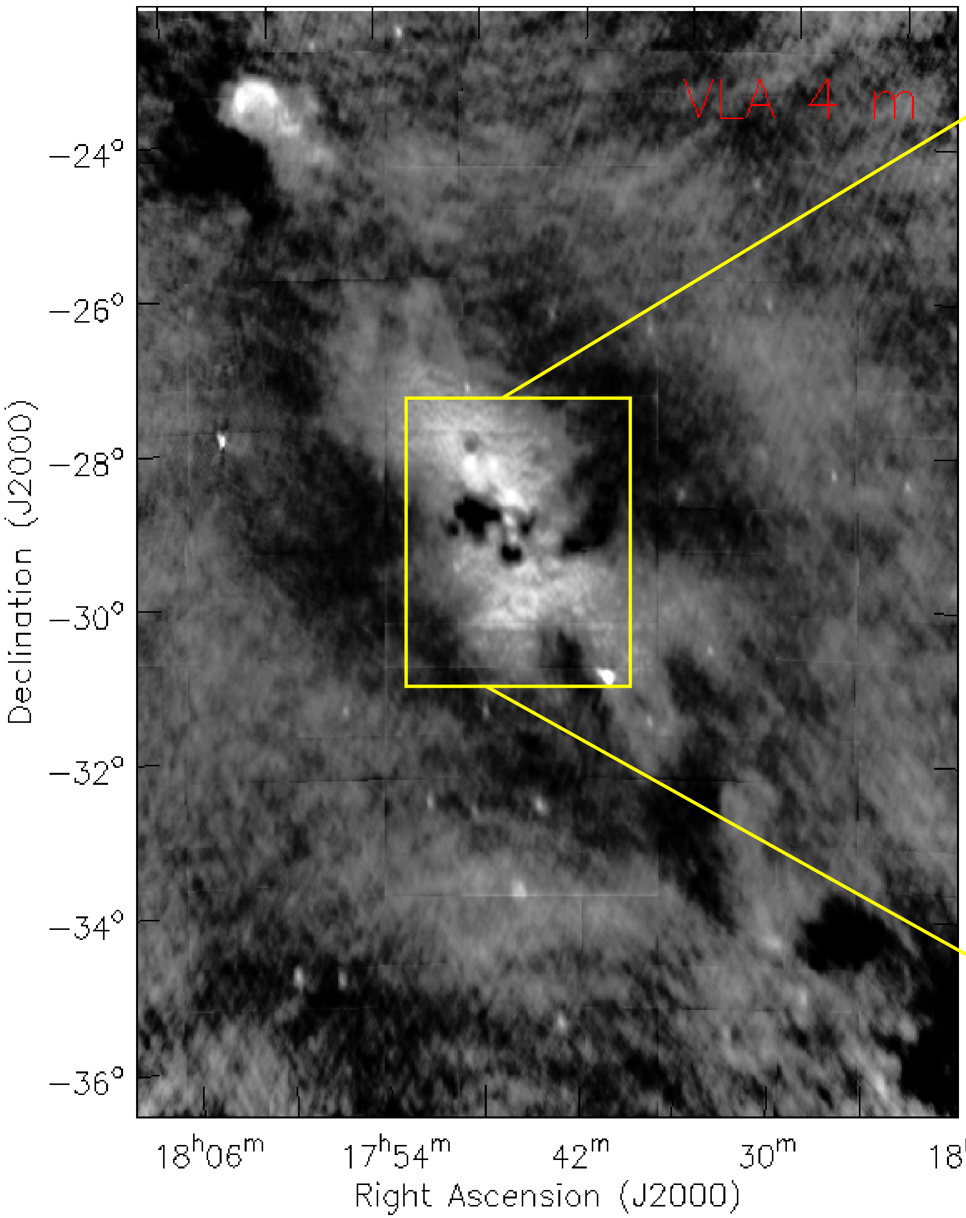
New GC Nonthermal Filaments

- NTF Results
  - New and improved 330 MHz GC image
  - Orientation of newly discovered NTF's suggests a magnetic field structure more complicated than a simple dipole
  - Detecting only the peak of the NTF luminosity function?
  - A significant increase in sensitivity provided by LOFAR or SKA might detect hundreds of NTFs.

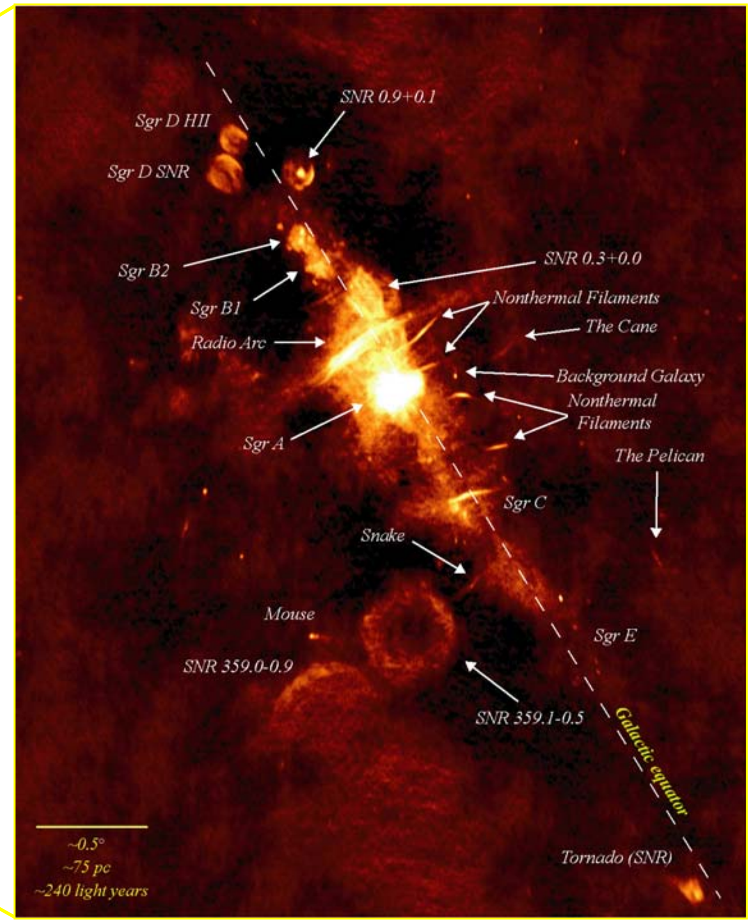
VLA 74 MHz (4 m) GC Image

(courtesy Crystal Brogan & Michael Nord)

ν = 74 MHz



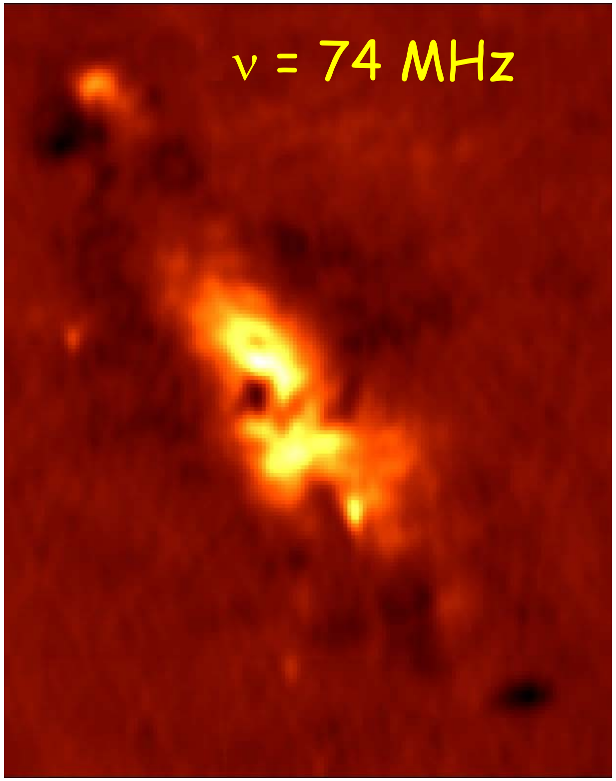
ν = 330 MHz



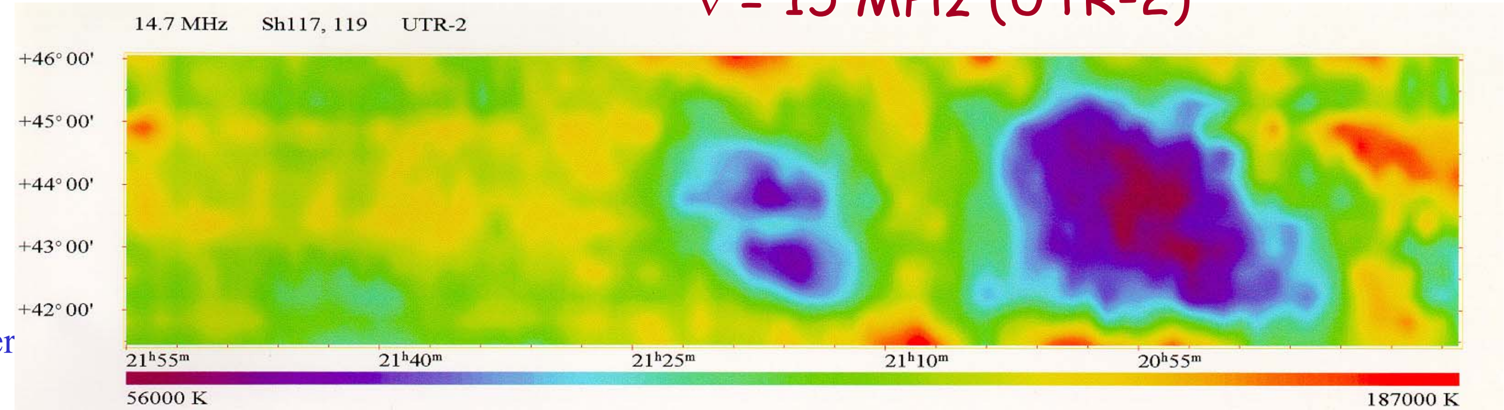
Mapping the 3D Distribution of the CR Electron Gas:

Clues to Propagation & Origin

- Use Galactic synchrotron emission to trace CR electron gas, as suggested by Longair (1990), Webber (1990), & others
- High ν measures total column density, confused with thermal & discrete sources
- Low ν see only the synchrotron emission, HII regions provide kinematically well determined path lengths, allow determination of 3D distribution
- Combine with γ-ray, HI emission for more information: Galactic B field



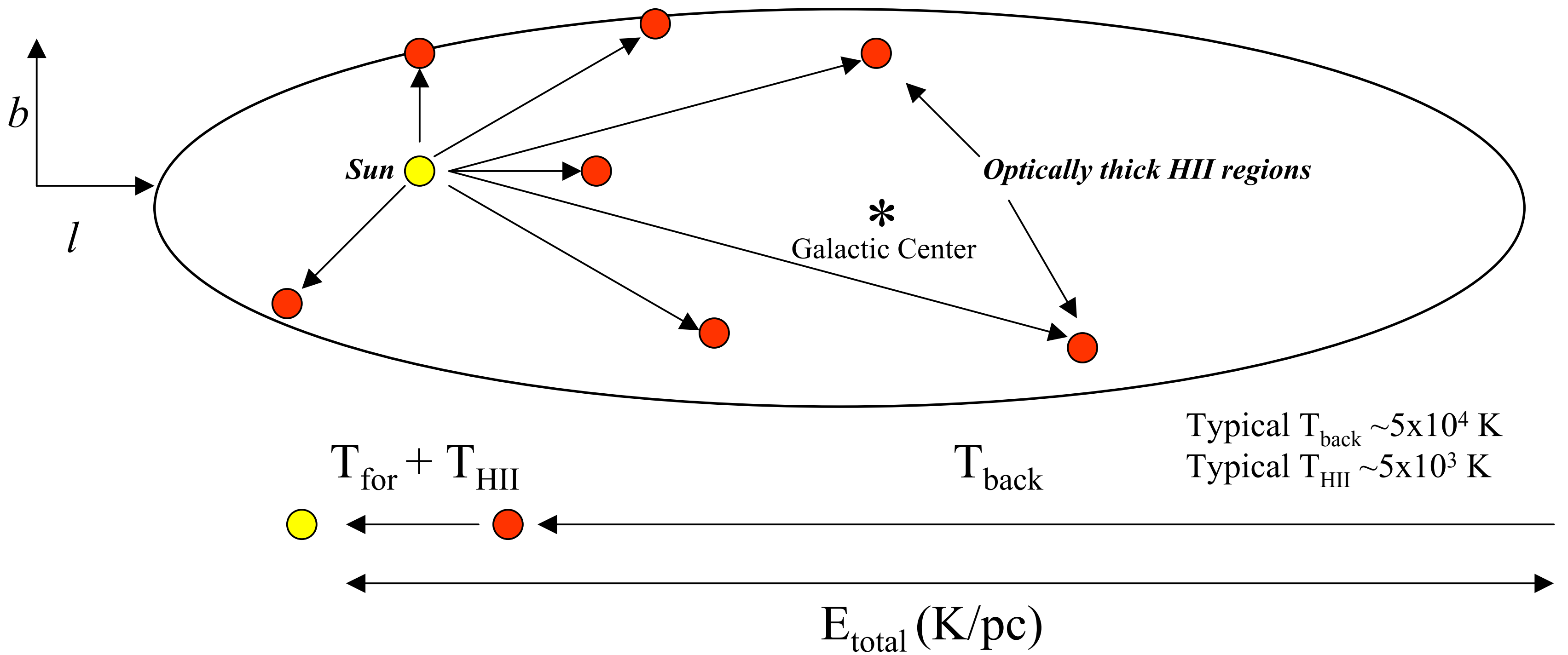
ν = 15 MHz (UTR-2)



Galactic Cosmic Ray Tomography

Use Galactic HII regions at known distances

Measure foreground, background, & total synchrotron emission along many lines of sight



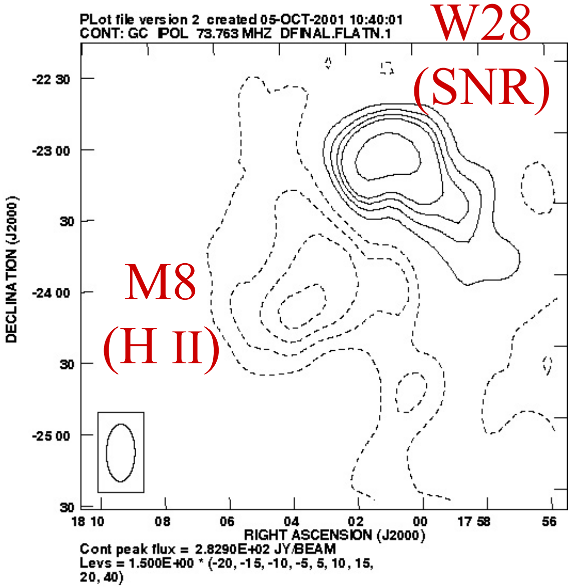
Typical 30 MHz absorption "hole" flux for 10" HII region: ~0.5 mJy outer Galaxy, ~3 mJy inner Galaxy

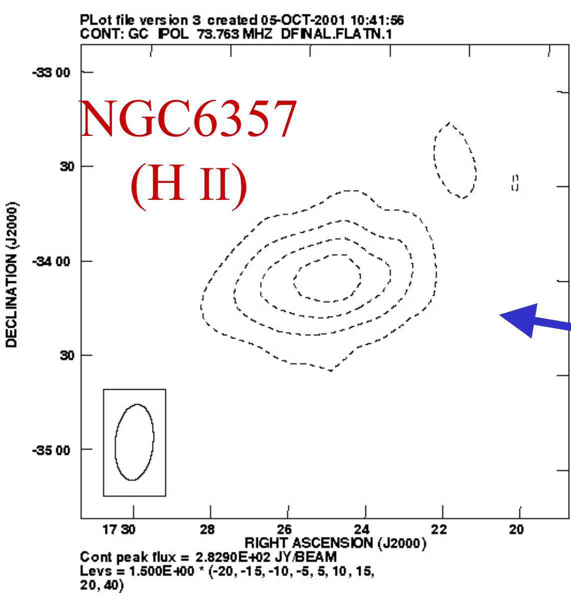
(at least 1000 Galactic HII regions of this scale)

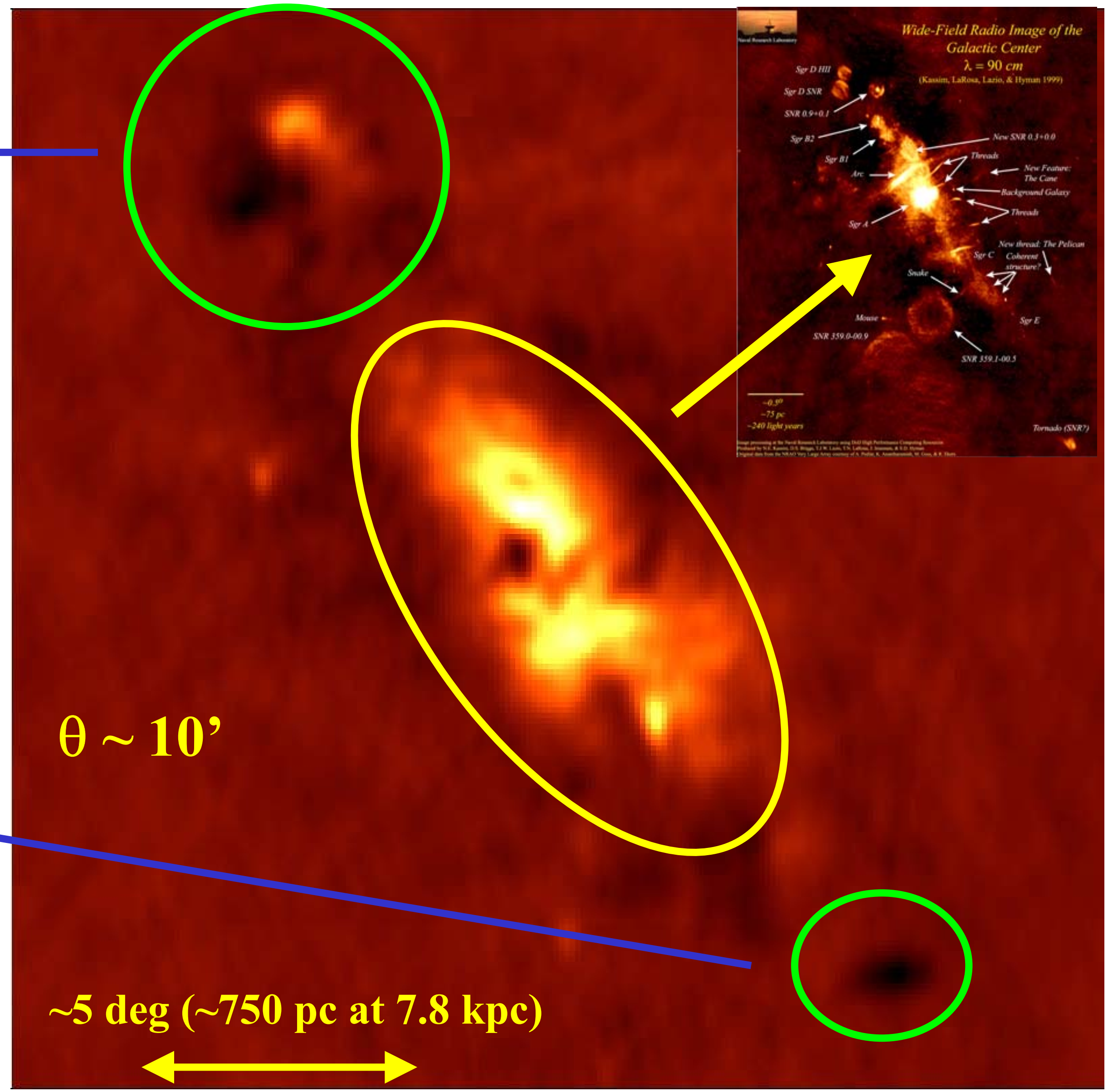
Current census: perhaps 2 dozen LOFAR census: hundreds to thousands

74 MHz GC: HII Region Absorption

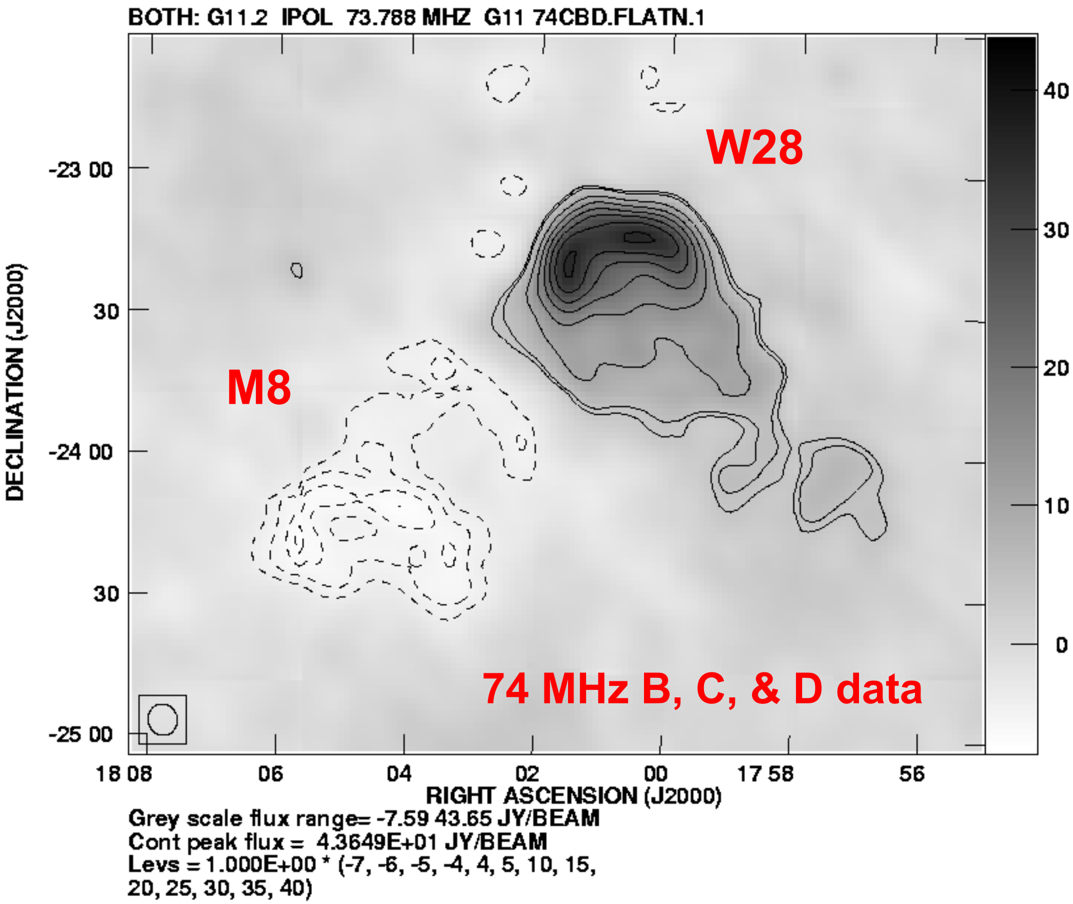
(Nord et al. 2002)

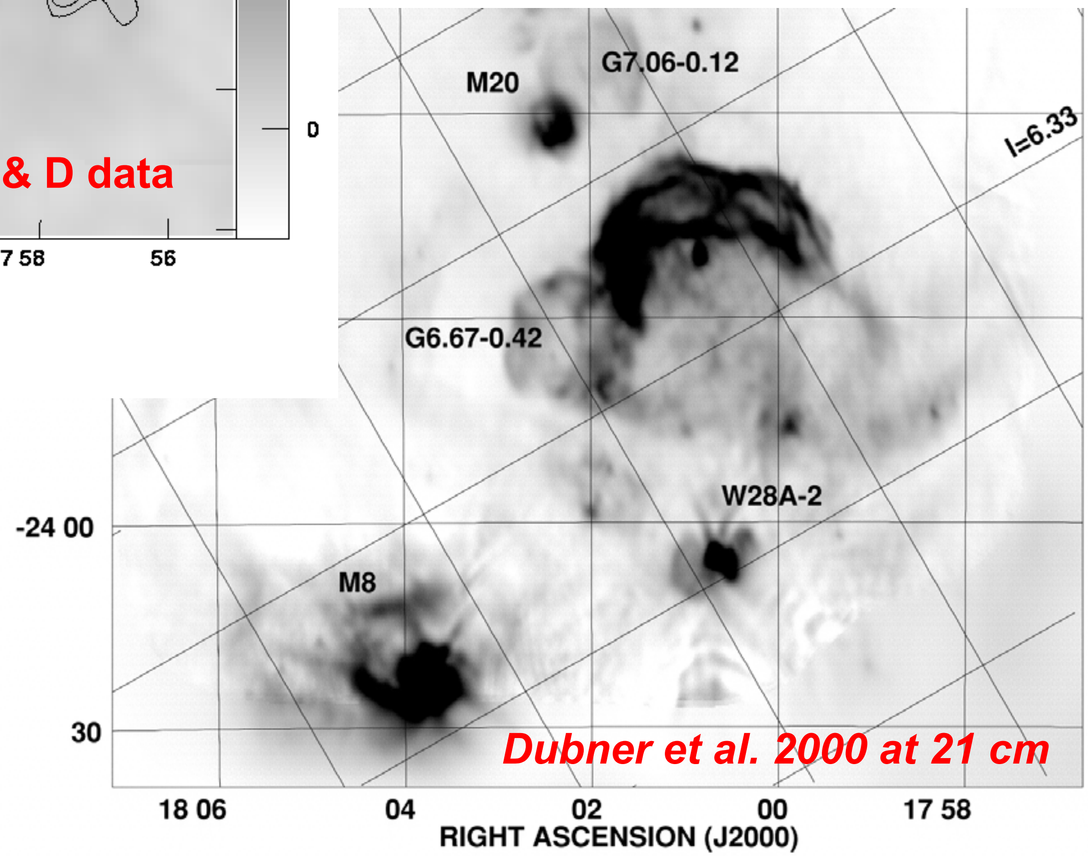






HII Absorption Holes
(slide courtesy C. Brogan)

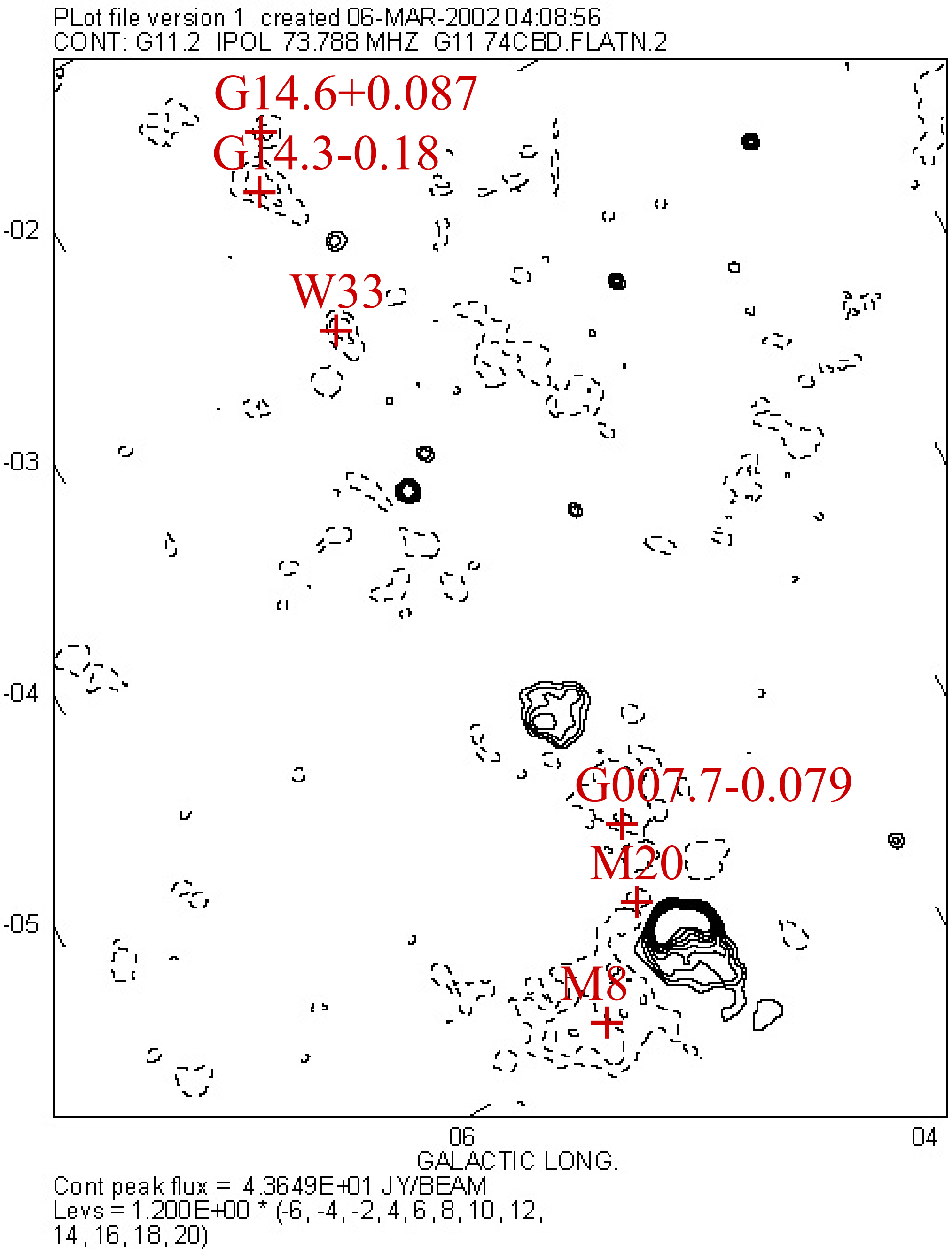




Nord et al. 2002, in prep. Estimate that the foreground CR temperature is 3500K and the emissivity is 1.9 K/pc using previous data for the distance and T_e of M8.

(Nord et al. in preparation)

ν = 74 MHz

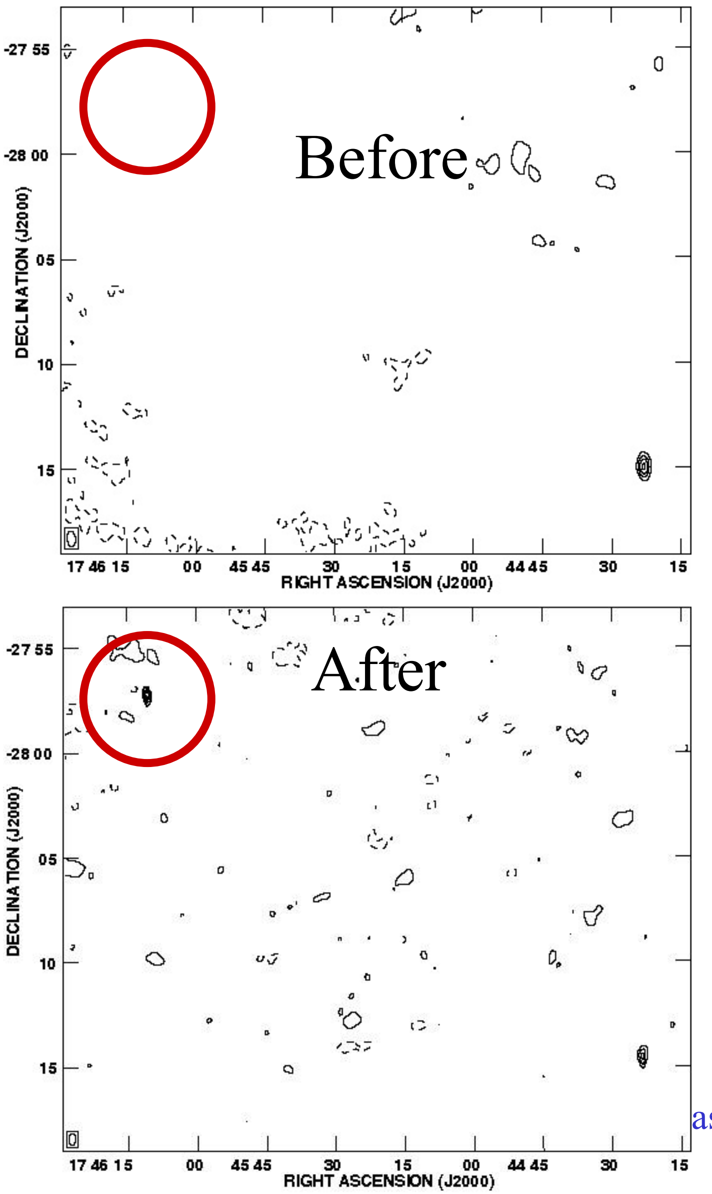


Various HII regions in absorption

Galactic Center Transients

(Hyman et al. 2002)

ν = 330 MHz



- Radio afterglows (GRBs, SNe, magnetars, …)
- Prompt GRB and/or SNe emission
- Giant pulses from pulsars
- Coherent burst emission (stars, planets)
- Microquasars
- AGN flares
- Microlensing events
- Cosmic-ray showers
- LIGO events
- Evaporating black holes
- …

Pulsars

- Detecting fast (steep-spectrum) pulsars ⇒ Imaging searches can remove significant biases
  - tight binaries
  - highly dispersed, distant PSRs
  - submsec PSRs?
  - possibly detect PSRs in M31
- Probe PSR emission mechanism
  - explore faint end of PSR luminosity function

    Find many more PSRs?
  - spectral turnovers near 100 MHz (“vanilla” 1 second PSRs vs. millisecond PSRs)
- New SNR/PSR associations

  Deep, high surface brightness imaging of young pulsars

Spectrum of 4C21.53: 1st (& still fastest known) msec pulsar

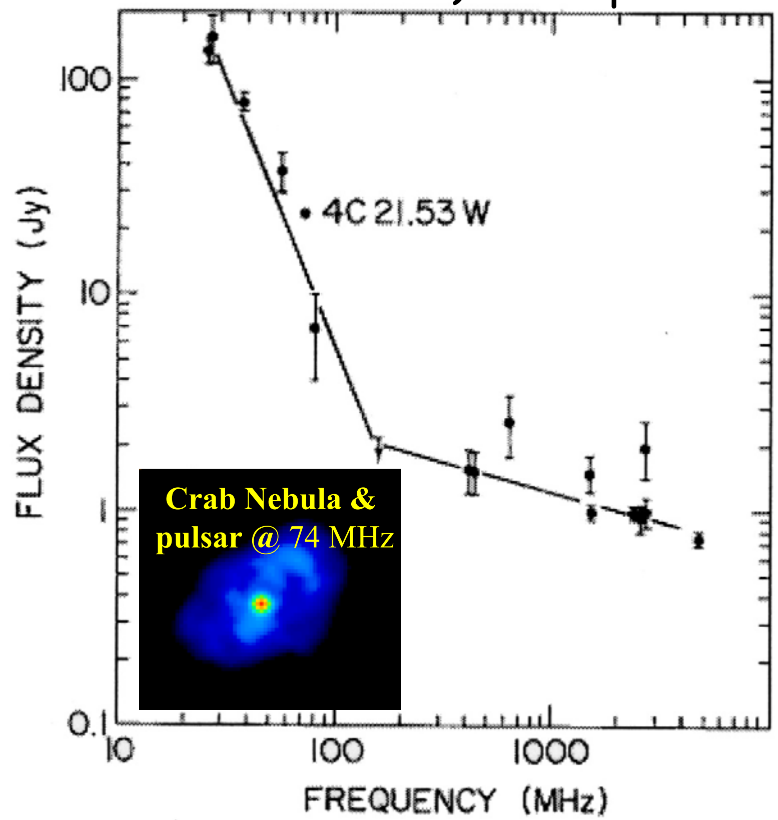
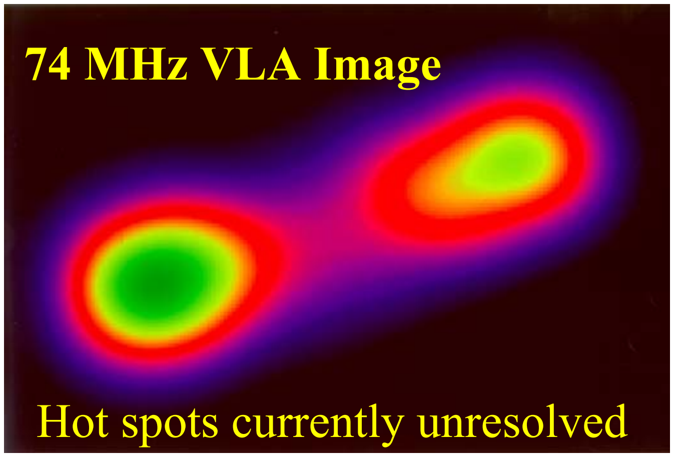


FIG. 2.—The radio spectrum of 4C 21.53W. Data are listed in Table 2. The solid lines correspond to spectral indices of −0.26 (ν > 150 MHz) and −2.44 (ν > 150 MHz).

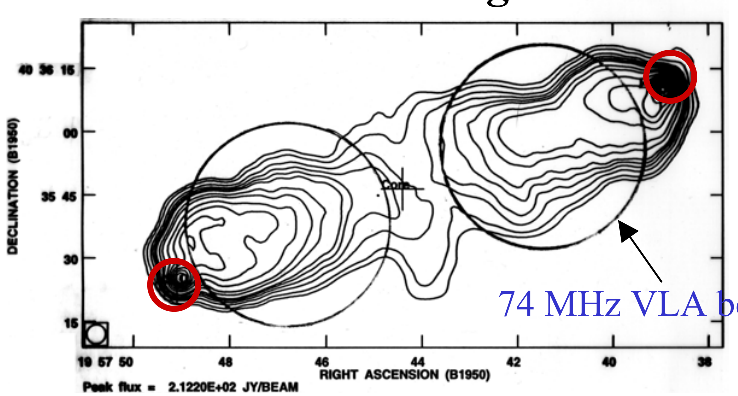
Drivers towards Higher Angular Resolution

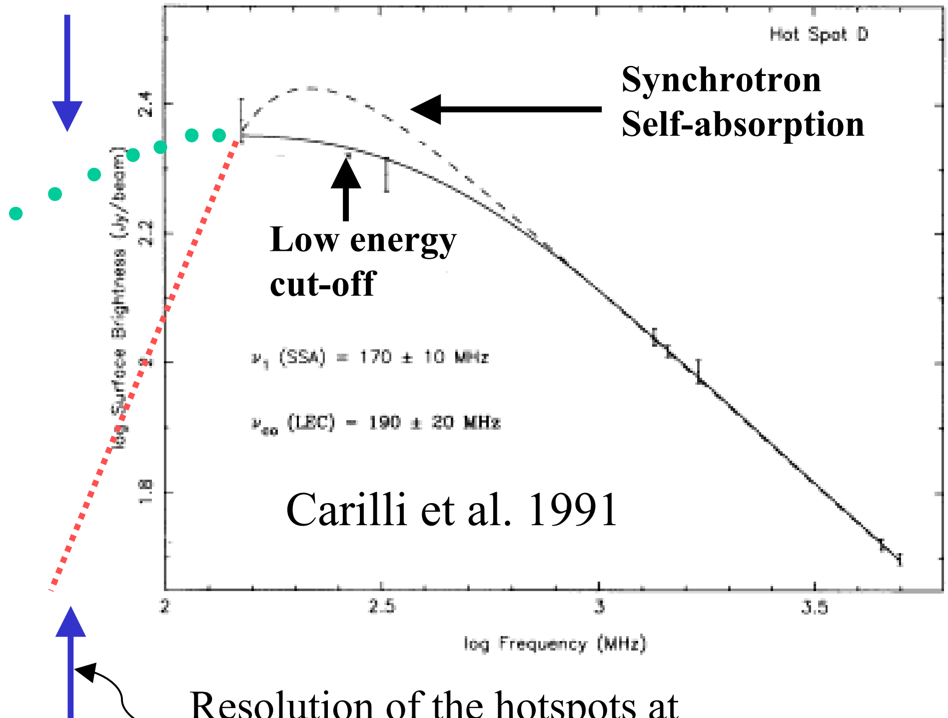
Cygnus A - pre PT link data



Kassim et al. 1996

330 MHz VLA Image



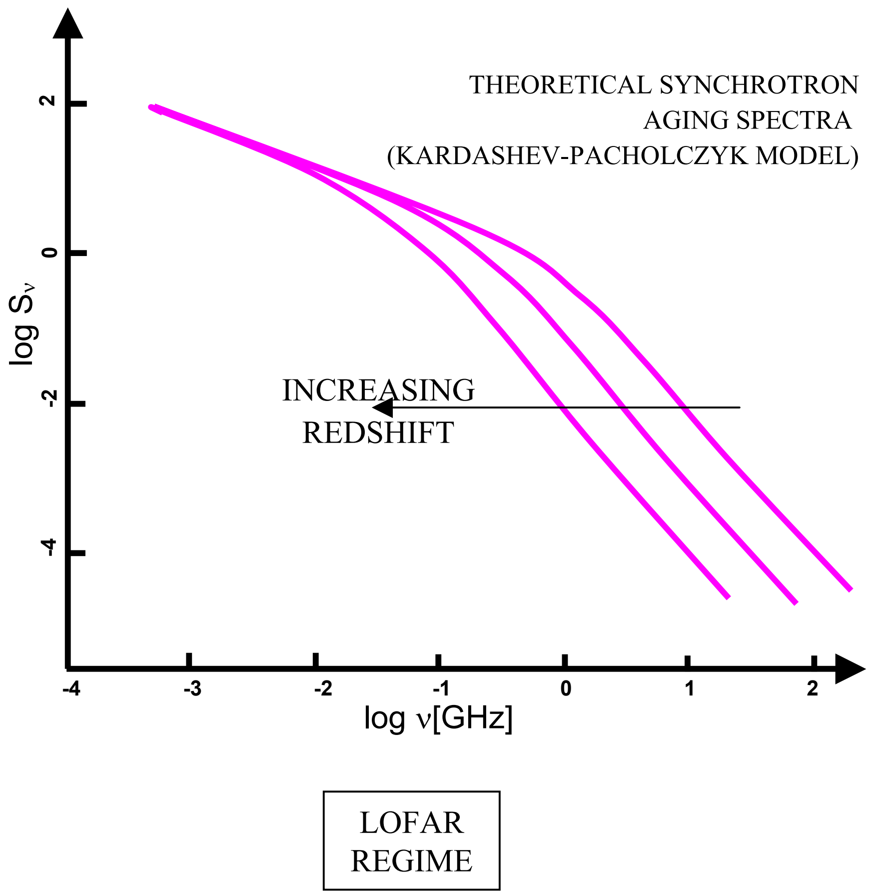


Resolution of the hotspots at
74 MHz will differentiate easily between
competing models for spectral turnover

Note also desire for broad-band

➔ "Hotspots"

High Redshift Galaxies: Natural Steep Spectrum Sources



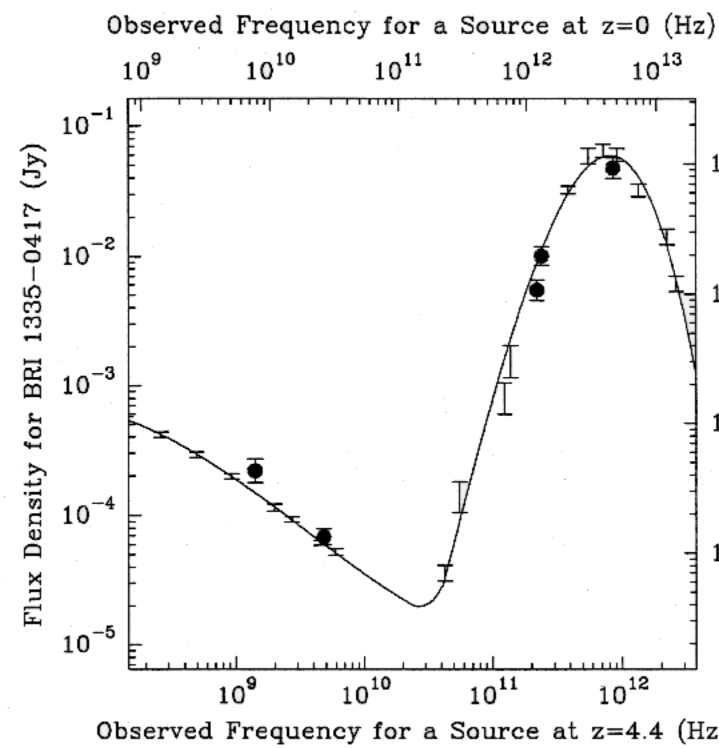
- Synchrotron losses steepen the high frequency spectrum of radio galaxies above ~ 1 GHz.
- At high z the spectrum is shifted to lower frequencies so that the entire *observed* spectrum is steep.
- Inverse Compton losses act similarly to steepen the spectrum, especially at high z since IC losses scale as z^4.

Redshifts of Distant Starbursts From Submm/Radio Spectra
(May Be Only Way to Do This Until NGST)

- HDF & Hubble implying star formation peaked near $z = 1$.
- SCUBA finding dusty starbursts apparently beyond this.
- SCUBA/MAMBO 350 GHz flux limits are a few mJy, implying 5 mJy at 150 MHz for $\alpha = -1$.
- At the highest z, IC losses may snuff out radio above 1 GHz

LOFAR may be the only answer

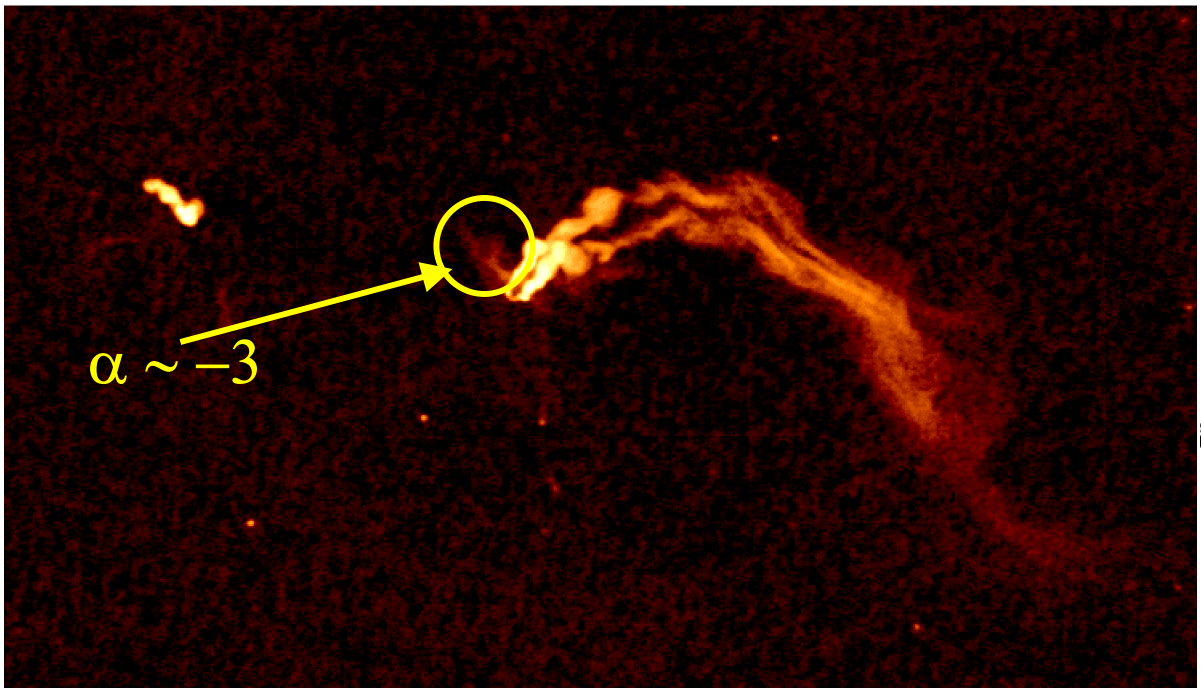
Radio - IR Spectrum of M82



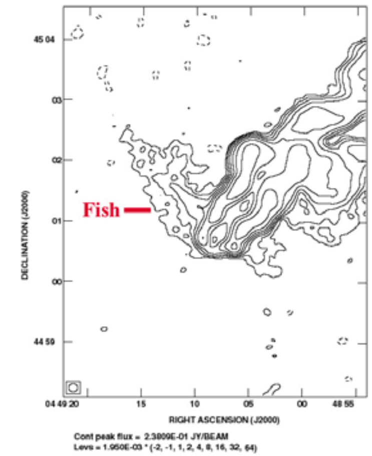
Carilli, Menten, & Yun 2000

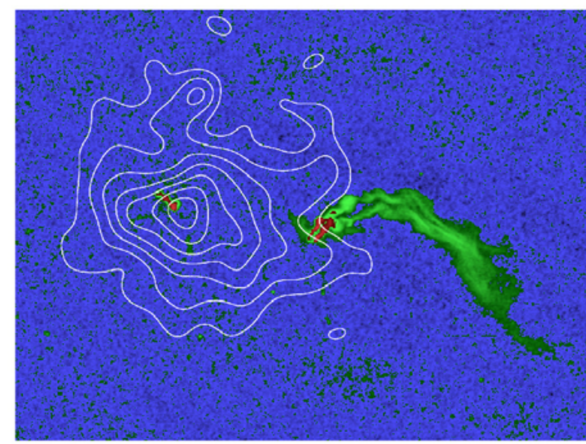
3C129 - Awakening Ultra - Steep Spectrum Relic?

ν = 330 MHz



Lane et al. 2002





X-ray contours centered on cluster center

74 MHz VLA: New Cluster/Relic System

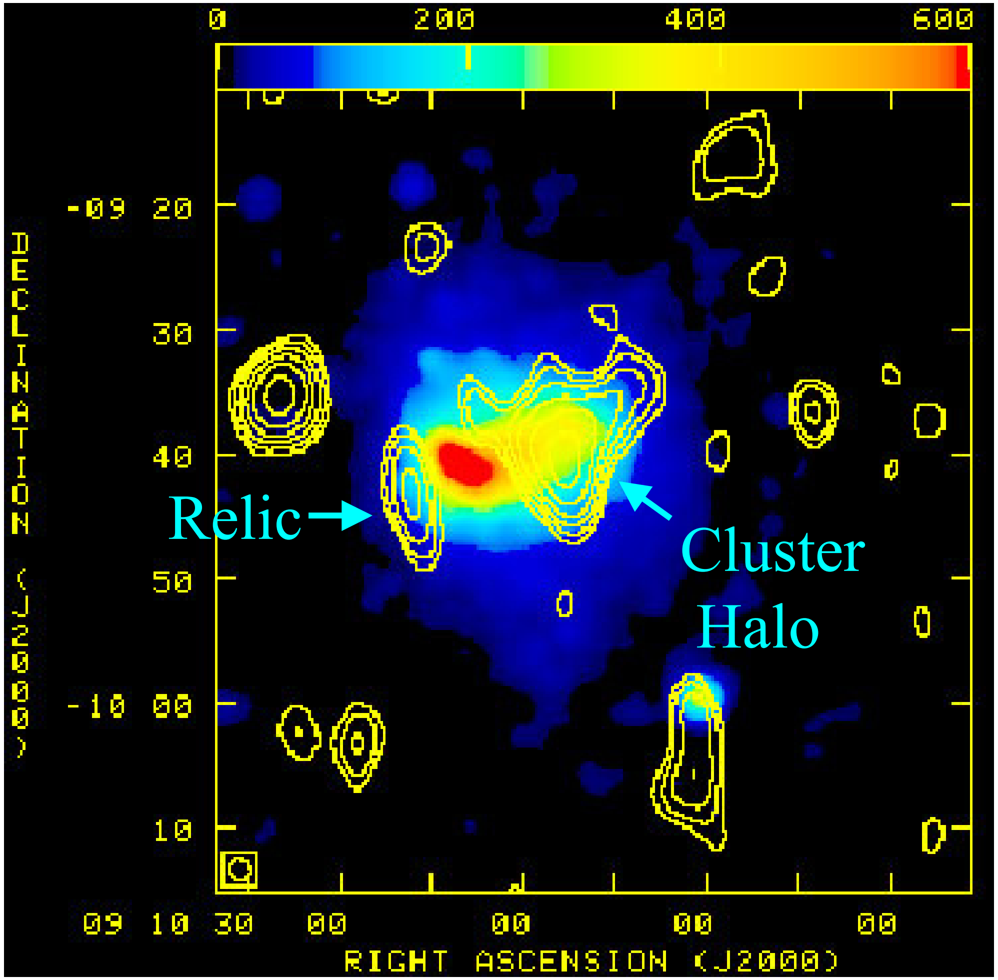
Clusters and relics probe relativistic particles/magnetic fields in intergalactic space and constrain theories of large scale structure formation in the Universe.

A new halo-relic system in the Abell 754 cluster of galaxies discovered with the 74 MHz VLA.

The derived spectrum and level of detection imply LOFAR may find more than 1000 such systems.

Color: ROSAT X-ray image
Contours: 74 MHz VLA image

Kassim et al. 2001

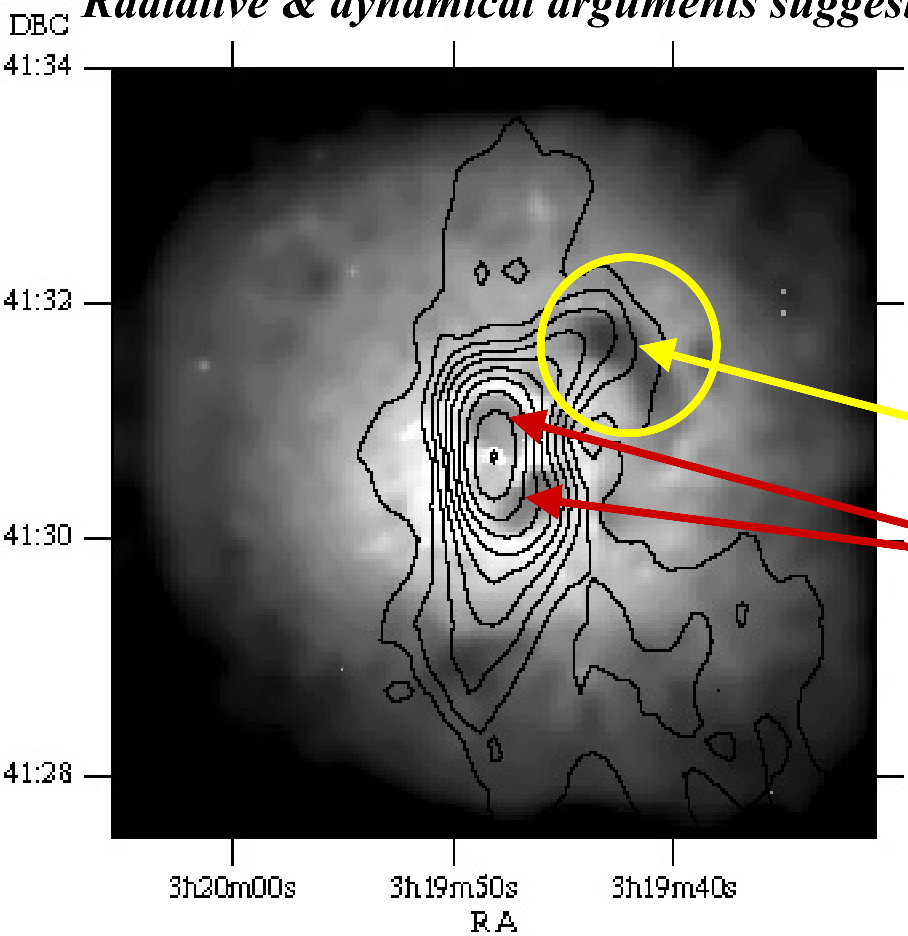


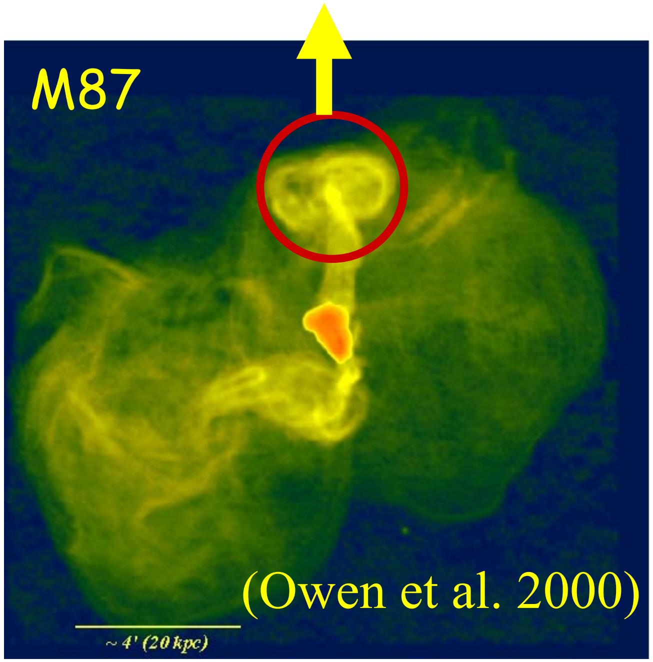
Perseus A at 74 MHz:

Buoyant Bubbles of Relativistic Electrons?

(Blundell et al 2000, Fabian et al 2002, MNRAS, 331, 369)

Radiative & dynamical arguments suggest k/f~350



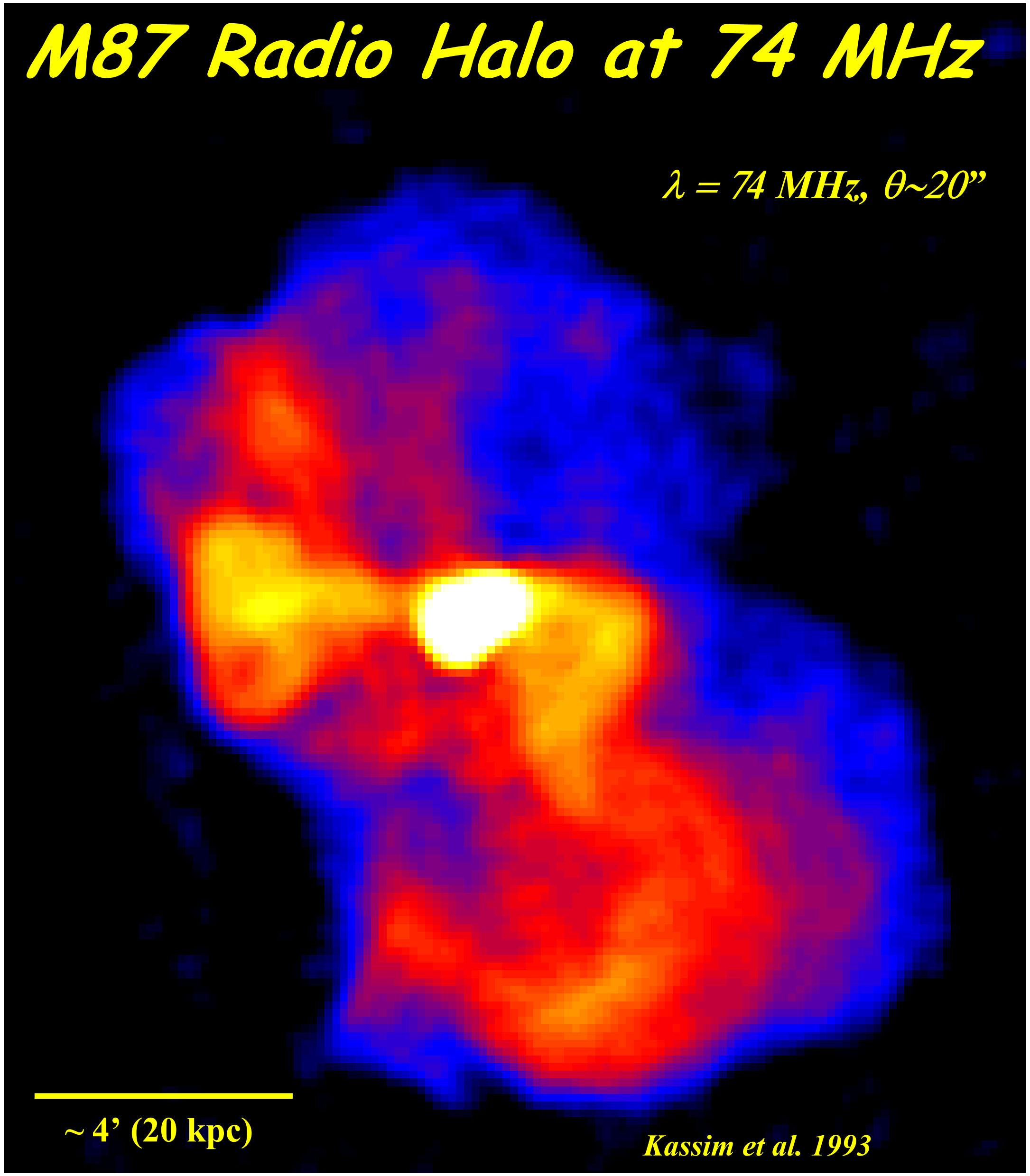


Steep spectrum radio emission coincident with Chandra X-ray bubble: lifetime of synchrotron Emission matches dynamical lifetime of bubble

X-ray bubbles coincident with jets of 3C84 radio galaxy

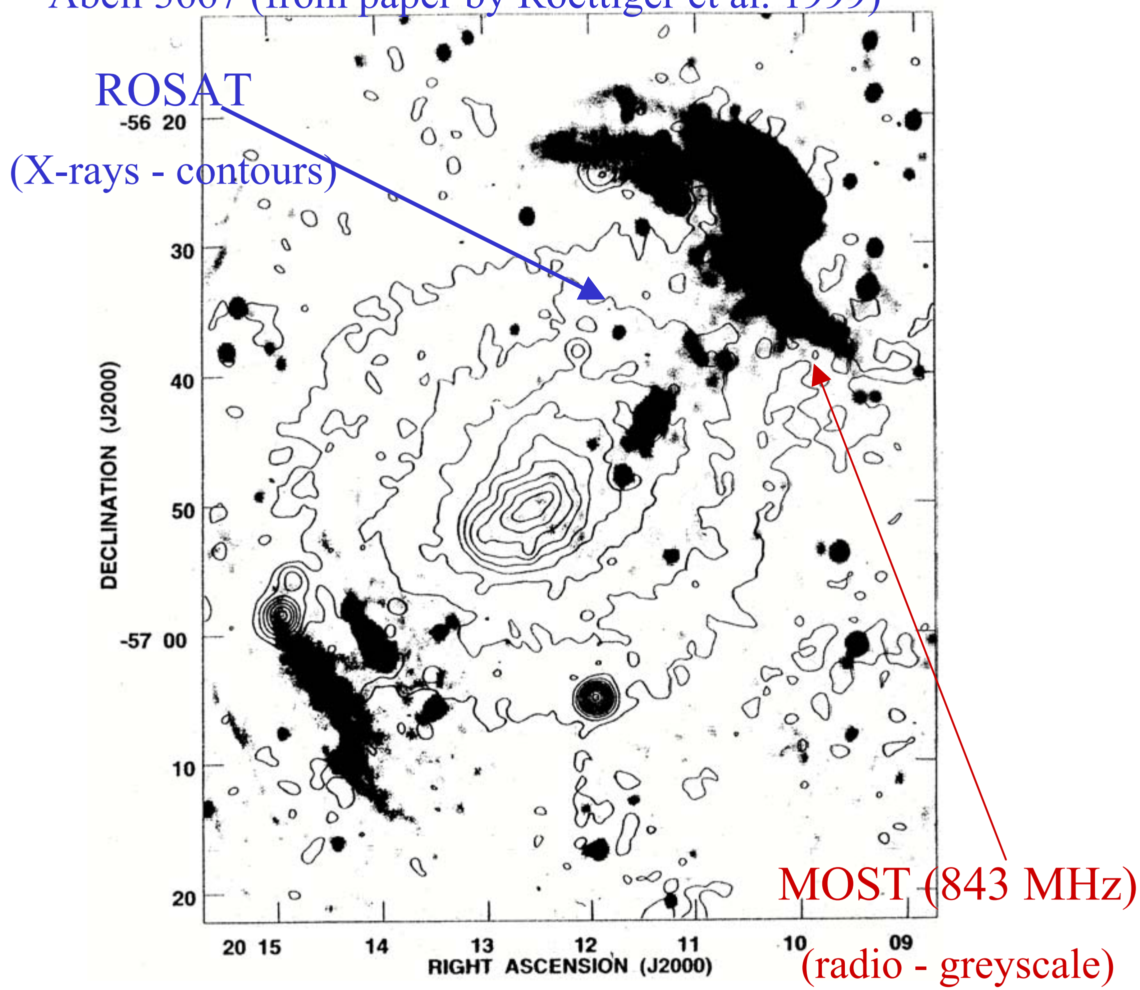
Can bubbles:

1. Solve cooling flow crisis?
2. Transport magnetic fields?


M87 Radio Halo at 74 MHz
λ = 74 MHz, θ~20"
~ 4' (20 kpc)
Kassim et al. 1993

Cluster "Relics": Shocks in Clusters of Galaxies

Abell 3667 (from paper by Roettiger et al. 1999)



- The steep spectrum radio emission from the shocks formed by infalling matter on to the cluster core.
- Physical parameters derived from such observations can provide physical constraints on models of large scale structure formation in the early Universe.
- Many more such structures presumably exist in the radio, but existing low frequency instruments have not had the sensitivity to detect them.
- Seen in merging clusters.

Cluster Sky like X-mas Tree for LOFAR!

(courtesy T. Enßlin – see also Enßlin & Rotgerring)

Fossil Radio Plasma in Cluster Merger Shock Waves

Enβlin & Brüggen (2001)

Expected Cluster Radio Relic Population

age of radio plasma: t
age distribution: $f(t)\,dt = q\,dt$
momentum cutoff: p_*

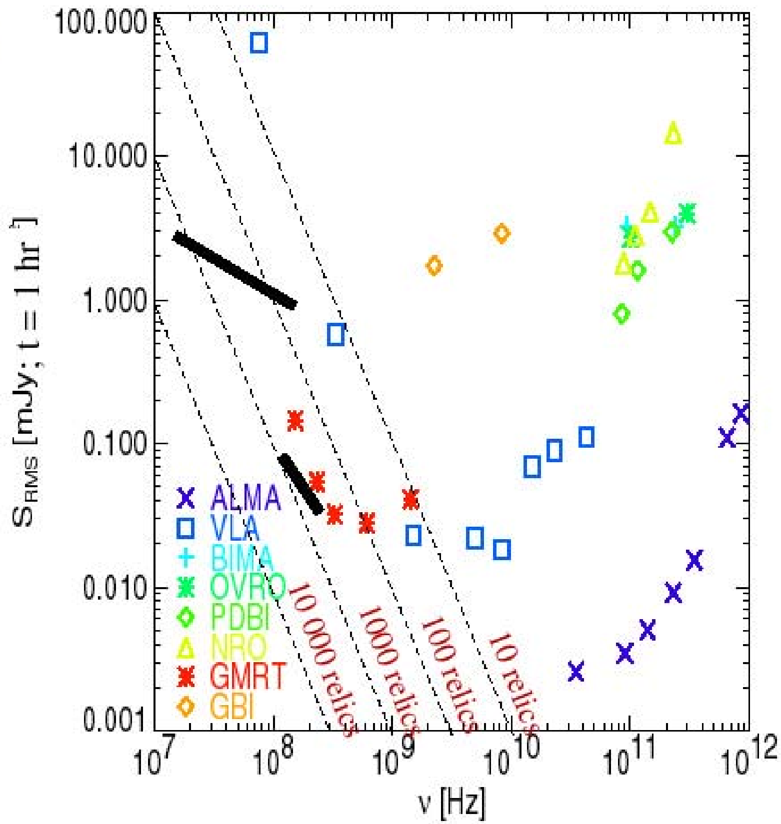
$$\text{Sync./IC cooling}: \frac{dp_*}{dt} = -a\,p_*^2$$

momentum cutoff distr.: $f(p_*)\,dp_* \sim p_*^{-2}\,dp_*$
frequency cutoff distr.: $f(\nu_*)\,d\nu_* \sim \nu_*^{-3/2}\,d\nu_*$

$$\frac{dN}{dL_\nu\,d\nu_*} \sim \frac{dN}{dL_\nu} f(\nu_*) \sim \nu_*^{-3/2} \left(\frac{L_\nu}{L_0\,\nu^{-\alpha}}\right)^{-\beta}$$

$$N(L > L_\nu, \nu_* > \nu) \sim \nu^{-\alpha\beta-1/2} L_\nu^{-\beta} \sim \nu^{-2} L_\nu^{-2}$$

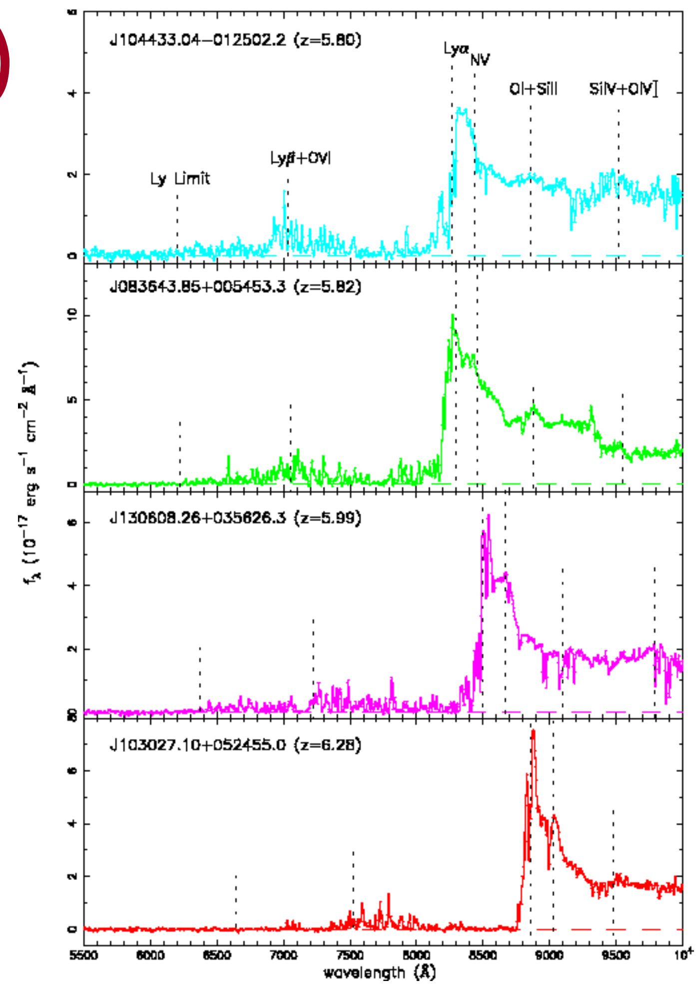
for typical radio spectral index $\alpha = 0.75$
and radio luminosity function slope $\beta = 2$.



Epoch of Reionization: $z \approx 6$ (H I at 200 MHz)

Universe made rapid transition from largely neutral to largely ionized

- Appears as Gunn-Peterson trough in high-*z* quasars
- Also detectable by highly-redshifted 21 cm H I line?
- WMAP Update: “first” of two re-ionization epochs near z~20 (HI at 70 MHz)??

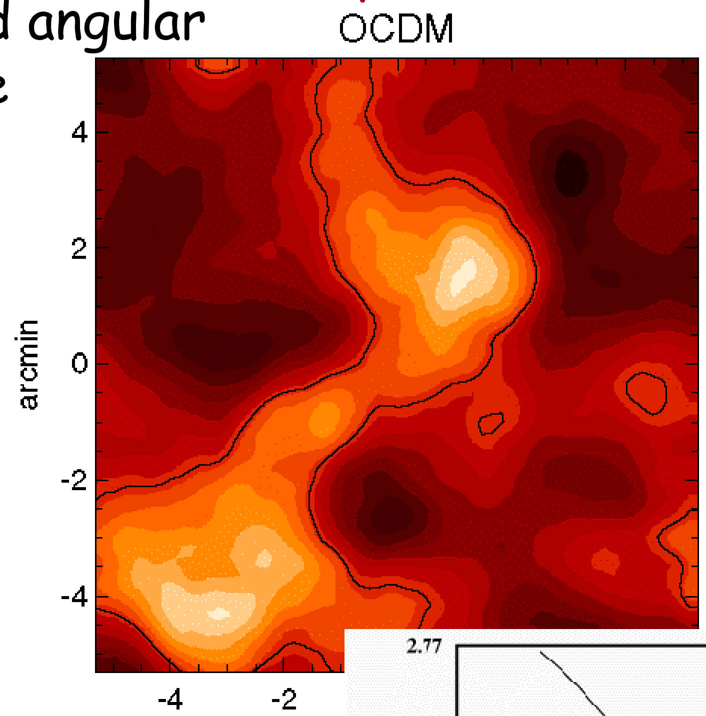


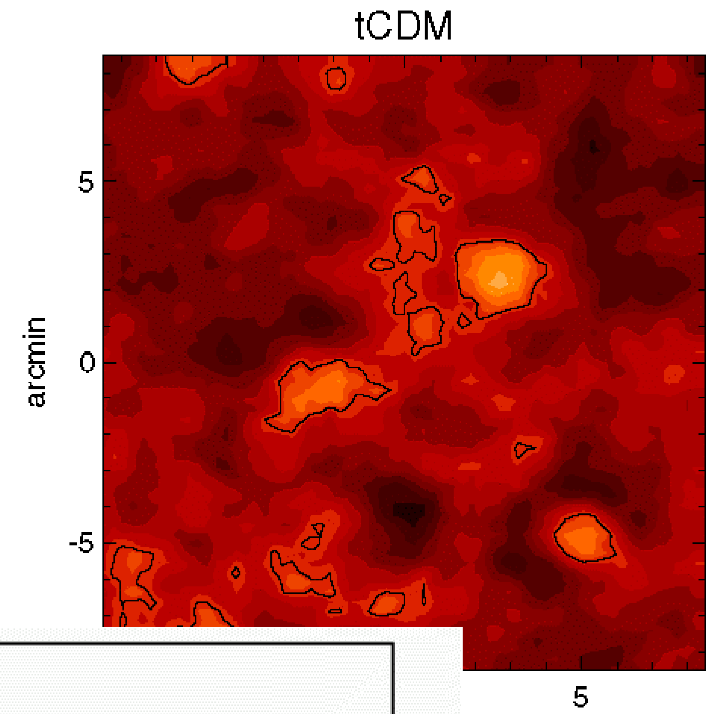
Becker et al. (2001)

Epoch Of Reionization

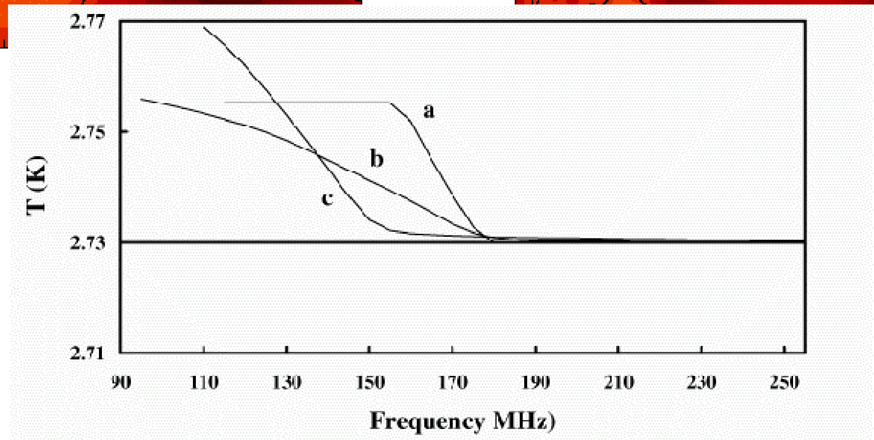
(predicted HI signatures)

Predicted angular structure



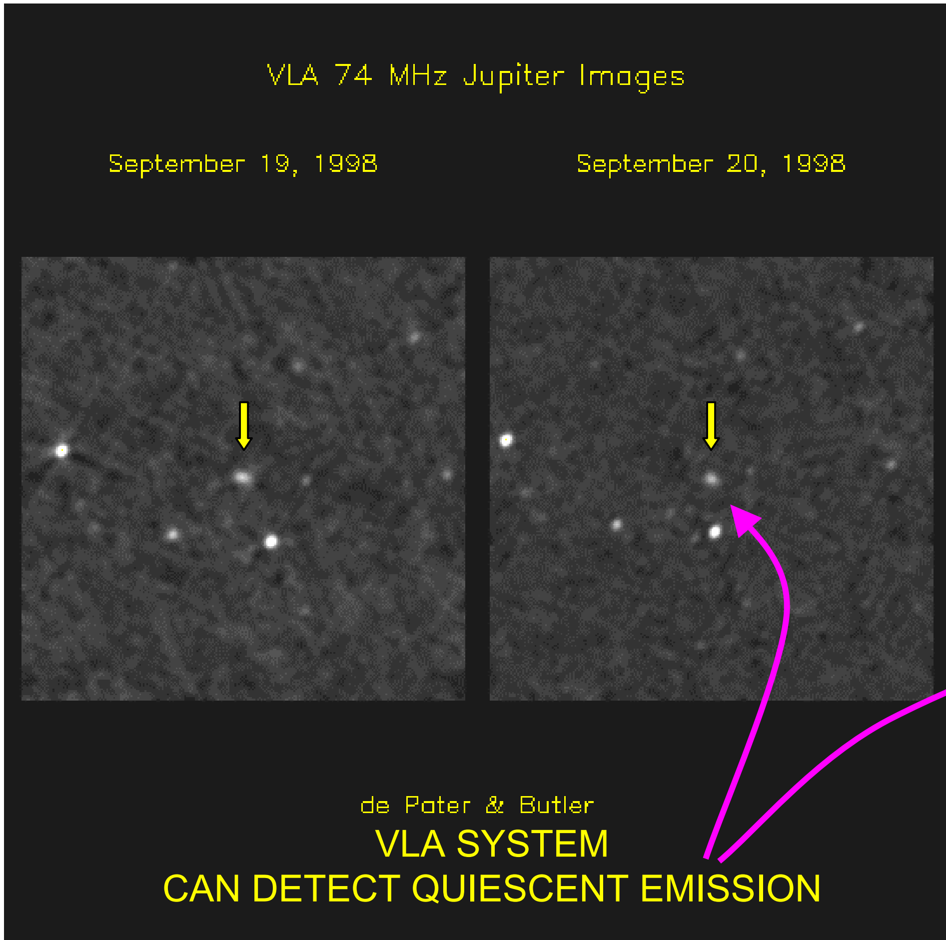


Predicted global spectral signature



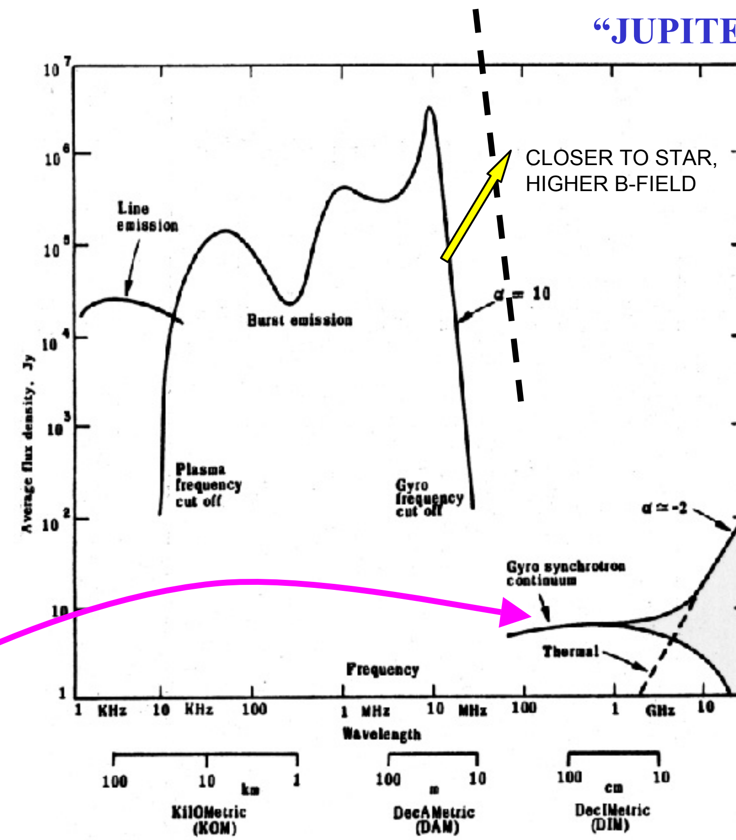
Bursts From Extra-solar Planets
Jupiter's Decametric Emission

Coherent cyclotron emission: complex interaction of Jupiter's magnetsphere with Io torus



LOFAR RANGE

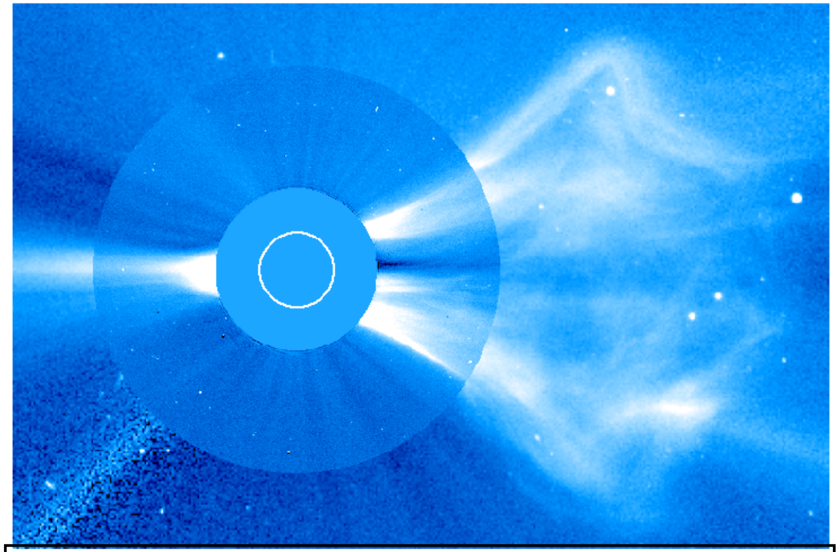
LOFAR COULD DETECT BURST EMISSION FROM DISTANT "JUPITERS"

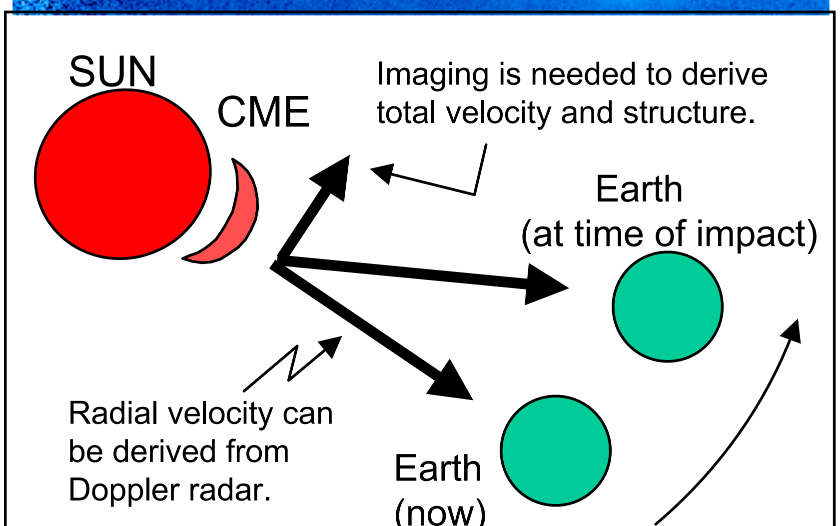


Jupiter: LOFAR will resolve emission

Coronal Mass Ejections

(Gopalswamy & Kundu)

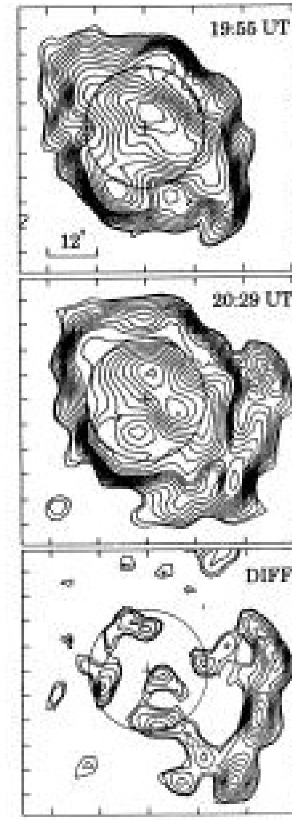




Coronal Mass Ejections (CMEs) are both significant science problems for solar physics and significant dangers for DoD and commercial space missions.

LOFAR could map out the structure of CMEs and determine space velocities to predict their impacts.

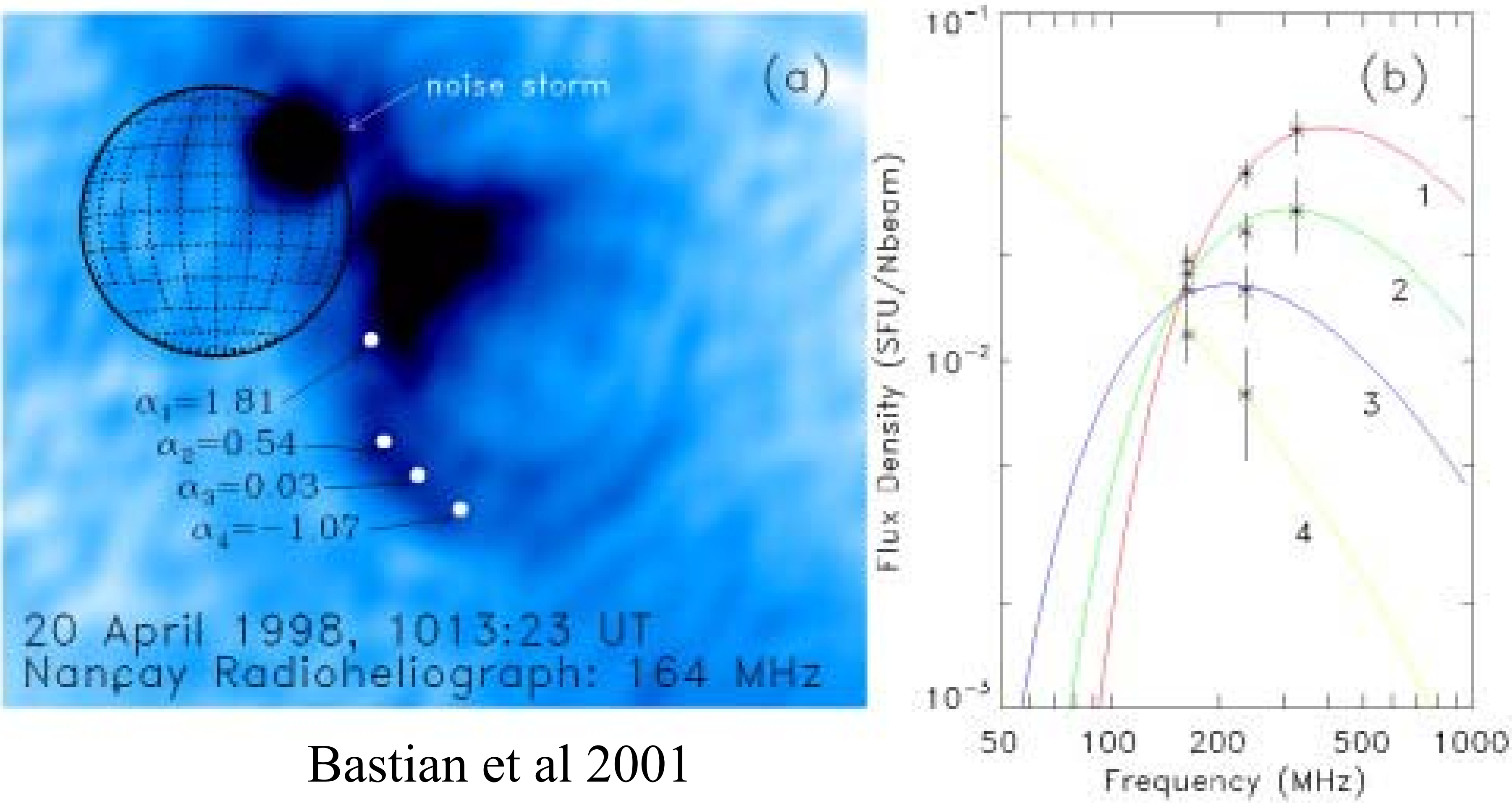
Although LOFAR is a passive instrument, it could also be used in combination with a suitably located radar transmitter to completely probe the density structure and space velocity.



Clark Lake (73.8 MHz)

CMEs: Synchrotron Emitting Sources

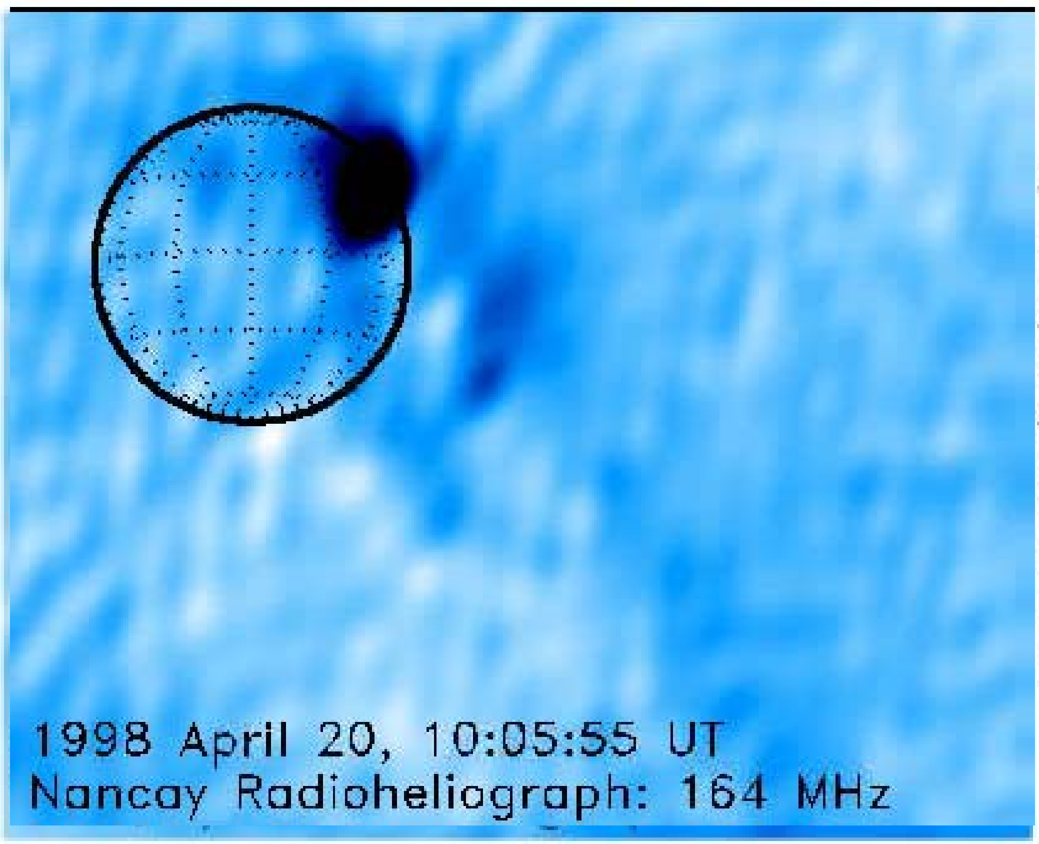
Nancay Image at 164 MHz

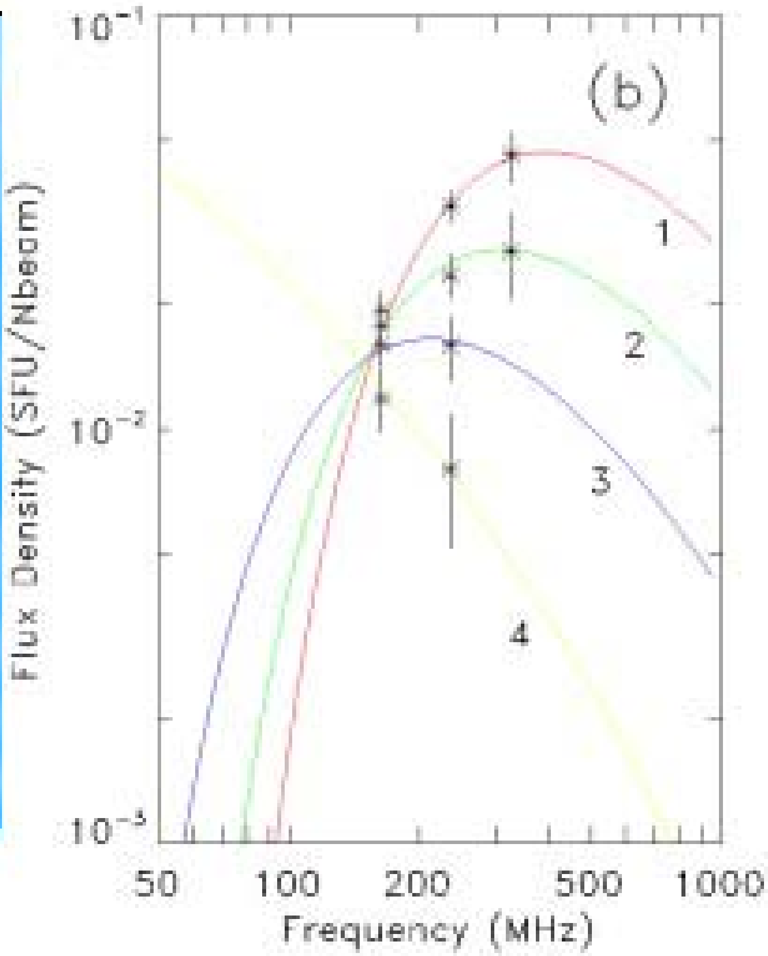


Bastian et al 2001

CMEs: Synchrotron Emitting Sources

Nancay Image at 164 MHz





Bastian et al 2001

Active Dipole Prototypes

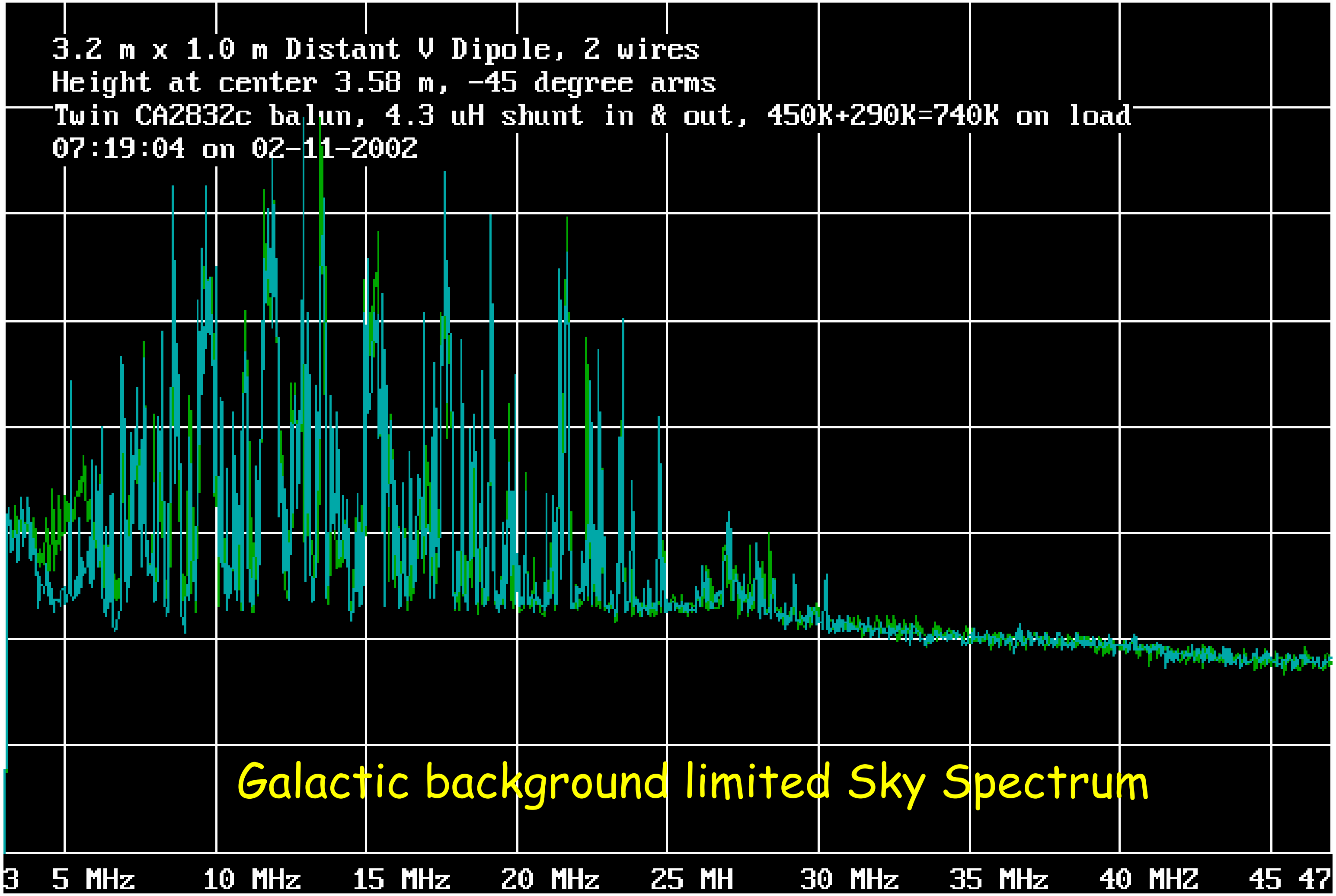
First LOFAR "Low-Band" (LB) prototype antennas – developed at Bruny Island Radio Observatory (Tasmania) by Bill Erickson

LB Low (~10-40 MHz) & LB High (~30-120 MHz) Antennas

Ground Screen

Active Dipole Sky Spectrum

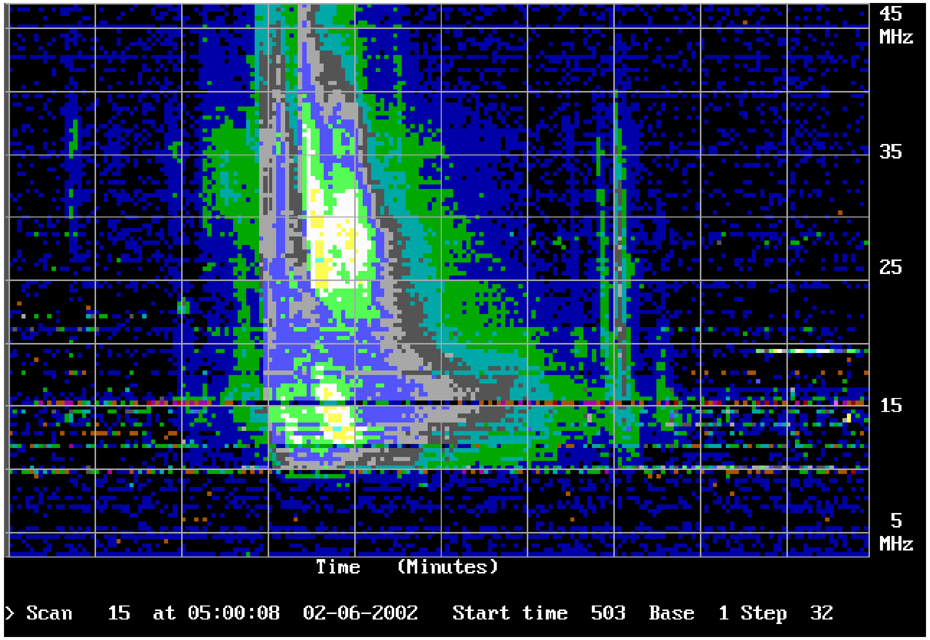
(from the NRL Low Frequency Test Array - near NRL in US)



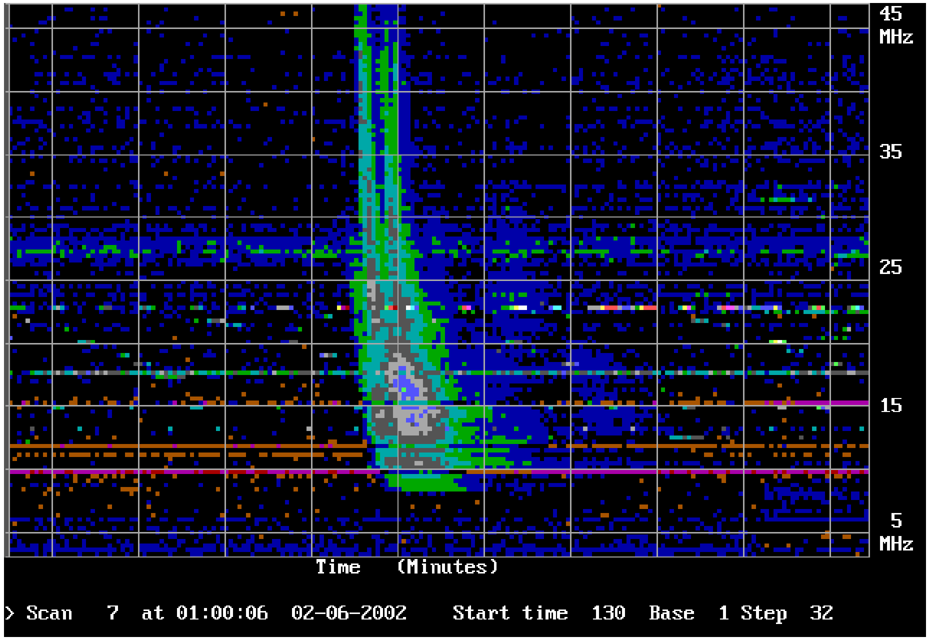
Active Dipole Solar Spectra

(from the NRL Low Frequency Test Array)

Type V Burst

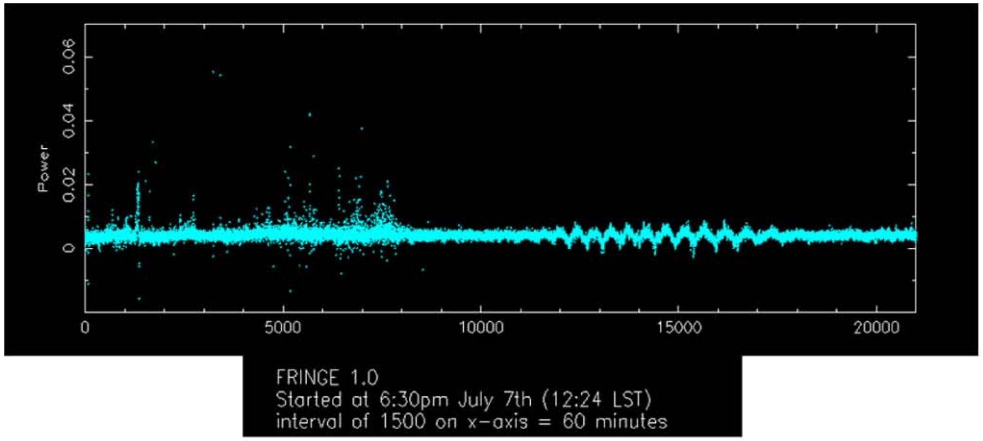


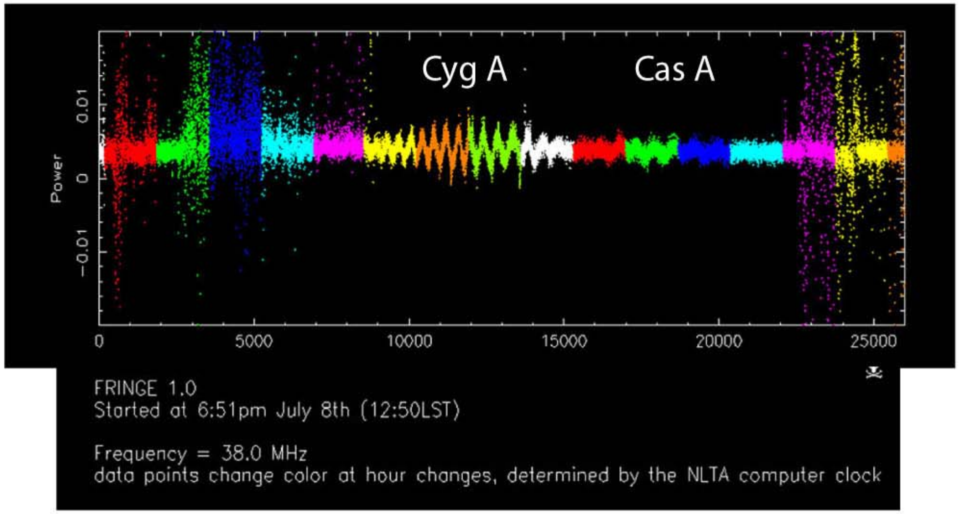
Type III Burst



NRL Low Frequency Test Array: First Fringes

Modified Mills Cross:
2 element interferometer:
8 elements in 2 groups of 4
~200 meter baseline





NLTA First fringes -- 07-08 July 2003

Key LOFAR Science Projects

- High Redshift Universe
  - Epoch of Reionization: detect and map spatial structure
  - unbiased sky surveys, select highest *z* galaxies
  - trace Galactic & intergalactic **B** fields, infalling shocks around clusters, new halos and relics
  - evolution & acceleration processes in radio galaxies
- Acceleration, Turbulence, and Propagation in the ISM
  - Cosmic Ray Electrons and Galactic Nonthermal Emission
    - map 3D distribution & spectrum, study propagation: clues for expected origin & acceleration in SNRs
  - New SNRs, PSRs, other discrete sources, including HII regions in absorption
    - constrain relative radial position of objects in Galactic complexes
    - study shock acceleration in SNRs
  - Deconvolve scattering & absorption effects
  - Galactic center studies – Sgr A*, map GC magnetic field, map halos & outflows
- Bursting and Transient Universe
  - broad-band, all-sky monitoring for variable/transient sources (GRBs, etc …)
  - search for coherent emission sources; e.g., stars, quasars, exoplanets
- Solar-Terrestrial Relationships
  - study fine-scale ionospheric structures, image Earth-directed CMEs (as radar receiver)
  - solar passive emission studies, trigger higher frequency targeted observations

LOFAR science plan recommended by (US) National Academy of Sciences Astronomy Survey Committee in the Decadal Report.

LOFAR (Low Frequency Array) Concept

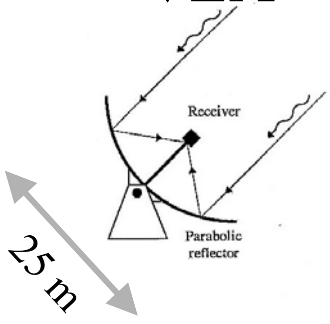
(http://www.lofar.org)

- **Inspired by 74 MHz VLA**, which demonstrated removal of ionospheric effects to achieve better sensitivity & angular resolution.
- Fully electronic, **broad-band antenna array**
- Basic element - active dipole receptors: $\Delta\nu \sim$ 10–240 MHz (3 scales of elements)
  - Low frequency limit: ionospheric absorption, scintillation
  - High frequency limit: λ^2 collecting area, better to use dishes above this
- "Stations" (dishes) are ~100 m diameter, comprised of ~200 receptors
  - Good primary beam definition, low sidelobe levels
- **Large aperture:** baselines $\leq$ 400 km (no limit on baseline length)
  - Good angular resolution, low confusion
- **Large collecting area**: $\geq 10^6$ m^2
  - 2–3 orders of magnitude improvement in resolution & sensitivity
  - 8"@15 MHz, 0.8"@150 MHz; < 1 mJy@15 MHz, < 300 μJy@ 150 MHz
- **Multiple beams**: advanced approach to astronomical observing

LOFAR Stations

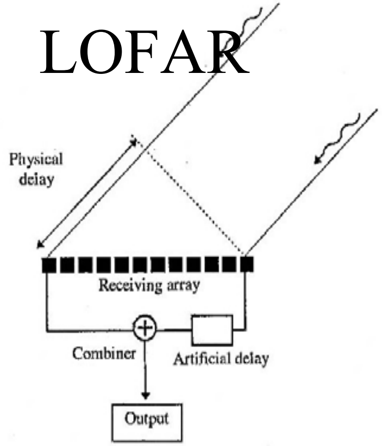
~200 Dipoles per "Station"
100 Total Stations over 400 km

VLA



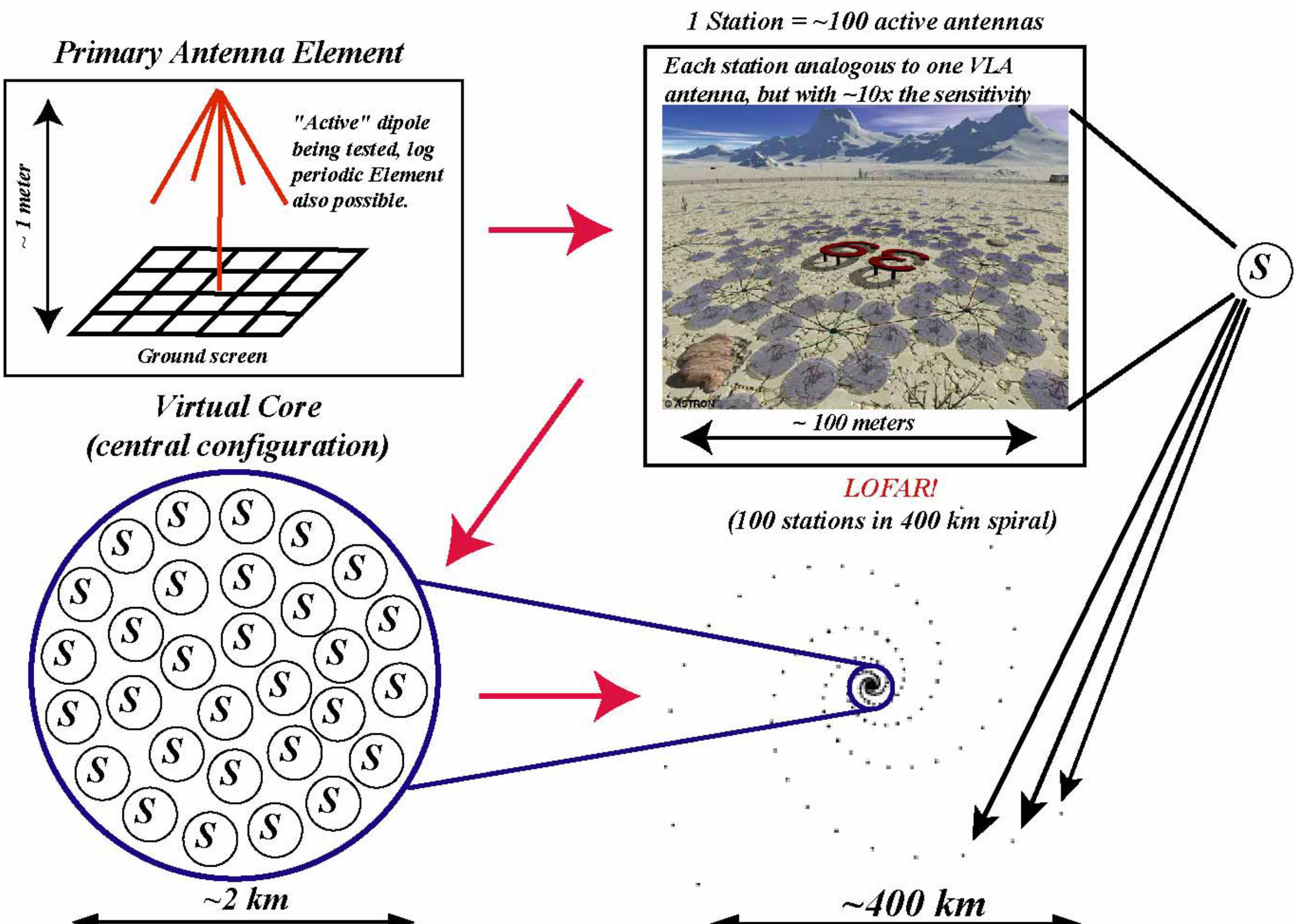
$A_e \sim 100\ m^2$

LOFAR

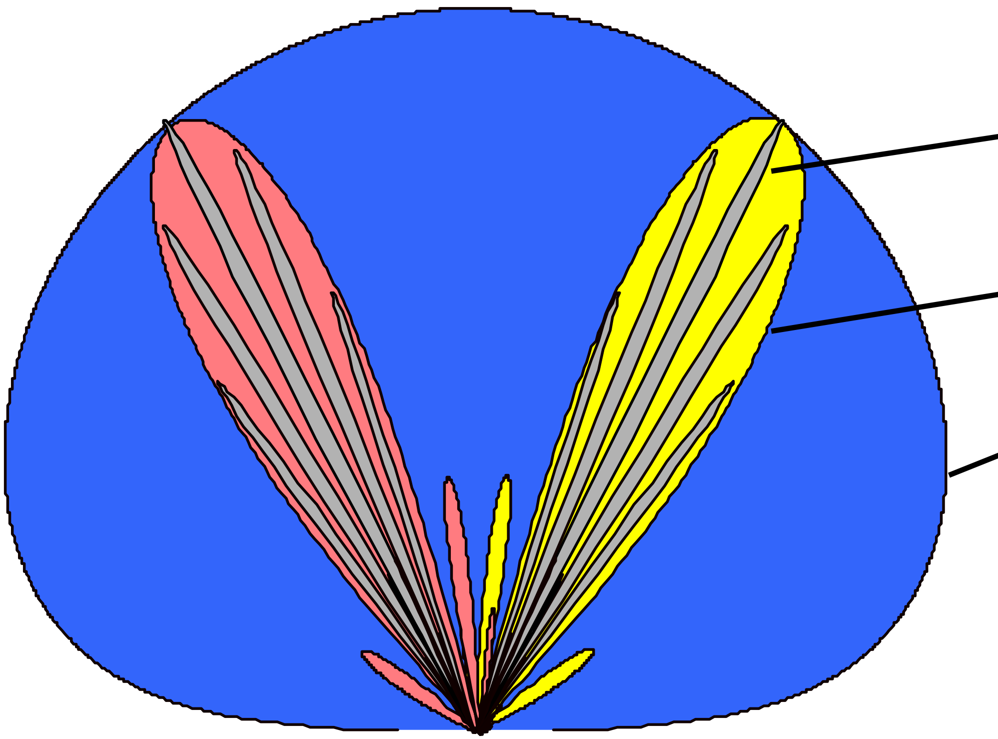


~100 m
$A_e \sim 1500\ m^2$

LOFAR Layout



Digital Electronic Arrays: Fast, Flexible, Multibeamed



Multiple, independent beams $\Rightarrow$ speed and flexibility
$\Rightarrow$ multiple, simultaneous science programs

Opening A New Window On The Universe

LOFAR Resolution & Sensitivity vs. Previous Capabilities